Thermomechanical Experiments and Modeling of Shape Memory Alloy Tension Springs; Critical and Liberative Analyses of Engineering Educational Systems

by

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For my parents, Frank and Donna Bowen,

And my grandparents, Don and Candy Frey.

This achievement is yours.

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The road to success surely doesn't go in a straight line. The completion of this thesis marks the arrival at a destination that, for nearly eight long years, didn't seem possible to reach. Indeed, the barriers created by existing social and institutional structures were simply not surmountable by my own brute-force efforts. Thus, the achievements of this thesis must be shared by all those whose labors, be they academic, avocational, or emotional, brought it into existence.

First and foremost, I must offer my most sincere appreciation to the members of my thesis committee and other members of the academic community who decided that this thesis should be written. I am indebted to Professors Krzysztof Fidkowski and Cindy Finelli, who both argued strenuously for the value of my work to the academy and encouraged its continued pursuit. Professors Ken Powell, Joi-Lynn Mondisa, Tony Waas, Veera Sundararaghavan, and Dr. Aaron Johnson then formed an interdisciplinary doctoral committee far outside the usual pattern for dissertation completion and not only accepted the unique situation but found merit in it as well. After my years in the technical research space had left my confidence as an engineer shattered, Professors Waas and Sundararaghavan enthusiastically affirmed that this work was not only valid but also contributory. My conviction that research was inherently toxic and unhealthy was defeated when Dr. Johnson showed me that research could specifically address the obstacles I and others were facing in our educational endeavors. Professor Mondisa completely reshaped my attitude towards research and rebuilt my confidence by proclaiming my academic abilities. Finally, Professor Pow-

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The technical work in the first part of my thesis would have ground to a halt (and, indeed, never gotten off the ground in the first place) without the labors of the best engineers within our community: our tech center guys. Aaron Borgman, Chris Chartier, Tom Griffin, Terry Larrow, Dave McLean, and Sam Reed not only performed the work necessary for this research to take place, but also provided instruction to build up my own skills as an engineer and support me within the academic machine. They even provided me physical care; Tom diligently dressed my wound and fixed my circuitry after I shredded my finger in a fan following electrocuting myself in the lab. (I also crashed my bike heading home that evening, so I'm going to try to wipe that day from my memories of graduate school.) Visits with Terry in the machine shop were the highlight of my days as an experimentalist; the quality of both his work and his companionship are unmatched.

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I am grateful to the College of Engineering at the University of Michigan for funding the qualitative study within this thesis via a Diversity, Equity, and Inclusion Faculty Grant and to Professor Jeff Sakamoto for supporting this project in addition to members of the committee. I am also enormously grateful to all of the undergraduate student participants on this project and the graduate student facilitators and note-takers: Sarah Bork, Jeffrey Horowitz, Alex Kate Halvey, Benjamin Silcox, Enrique Rodriguez, Leanne Su, Lea Marlor, Piper Sigrest, Robert Loweth, Alyssa Travitz, Jennie Paik, and Shannon Clancy. Without this incredible group of humans, this work would not have been possible, and I hope you all found an element of empowerment in your participation. I also want to thank Vidhya Aravind, whose expertise in organizing and facilitation was utilized to train our team of graduate students. Finally, I need to thank my colleague on this project and dear friend Joey

Valle, who helps me to become a better organizer and activist and who never stops fighting for a better world.

Within the University of Michigan graduate student community, organizing work in support of the students is housed in our labor union, the Graduate Employees' Organization (GEO). I am continually inspired by the labors and passions of each and every student who contributes to our collective power. It is only thanks to the uphill battles fought and won by graduate students with GEO that working class students such as myself have any chance to attain doctoral degrees at this university. This and any and all of my future academic accomplishments are made possible by the graduate student organizers who came before me, and future organizing will be the means by which the yokes of oppression are lifted fully from our communities. Solidarity Forever.

Finally, I must thank my friends and family for their endless love and encouragement both inside and outside my academic pursuits. While there are far too many people to list here individually, words cannot do justice to the grace that all of my friends both near and far have shown me over the past eight years. I value your friendship more than you know.

Thanks also to my sister, Mattie, who grew up while I was in graduate school. I promise to only be a little jealous of your amazing research, and I can't wait to see where you end up. Even though I don't understand anything you're talking about, I'm still your biggest fan.

To my spouse, Shardul: When I first started this program, I never believed that I would have a wonderful little family by the end of it. I appreciate you and our perfect furbaby, Sophie, every day, and I'm not sure what I did so right as to deserve you. Thank you for not only reading but also legitimately contributing to my work, not only supporting but also ordering me to chase my dreams, and forever choosing to be at my side as we reach for the stars.

To my Grandma and Grandpa Frey, the support you gave in order to allow me to pursue this degree is simply unfathomable. The fact that our society would ever require such a sacrifice is indefensible. I hope to one day prove that I am worthy of the faith you have shown in me, but I can only hope to make a fraction of the impact on the world as you have made on my life. This thesis is therefore dedicated to you, my mom, and my dad.

My parents are special people with a special task. I'm not sure what great transgression my parents committed for which they deserve the punishment of a lifetime dealing with my anxious antics, but they somehow never run out of the energy to listen to me squeal and scream, reaffirm my goodness, and then go out and fight on my behalf. They've even proofread big chunks of this thesis, which is probably something that no parent should ever have to do. They're just that good. Thanks, mom and dad. I am so privileged by your love.

Corey

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ABSTRACT

This thesis contains two areas of research. The first part contributes to the field of engineering mechanics. This research investigates the thermomechanical shape memory behavior of shape memory alloy (SMA) springs. As SMA springs undergo stress- and/or temperature-induced phase transformation, they experience varying combinations of axial, bending, and torsional stresses. A deeper understanding of the complex, three-dimensional state of stress within SMA springs, in combination with models of their actuation, will enable expanded application of SMA springs as actuators in a variety of industries. As such, the overall objective of this work is to comprehensively understand and model the thermomechanical behavior of SMA springs.

Experiments are performed on commercially-available SMA tension springs in order to explore the force-stretch-temperature design space. Two primary types of experiments are performed, isothermal loading and constant-load thermal actuation, on both virgin and cycled specimens. Experimental results are used to derive thermomechanical models that both describe the homogenized uniaxial behavior and the local, multi-axial distributions of stress and strain in the wire cross-section. Experimental studies of repeated thermal cycling are used to derive models both for virgin SMA springs and for their use in applications that require repetitive actuation.

Over the course of this work, detailed experiments enhance the understanding of the fundamental mechanics behind the actuation of SMA springs as well as the crystallographic phases through which the material passes. Additionally, thermome-

chanical models of SMA spring actuators enable expanded applications in aerospace, biomedical, and other industries.

The second part of this thesis addresses issues of equity within engineering educational systems. Higher educational programs in engineering today are seeking to correct disproportionately low enrollment and success rates of minoritized students. However, most diversity-related programming fails to address systems of structural oppression that cause particular students to be underrepresented in higher education. In this work, critical and liberative theories are applied to engineering educational systems to re-frame the problems with and goals of diversity, equity, and inclusion within engineering education from the lenses of Freirean critical theory, which is class-based, and other anti-oppressive theories based on race, gender, and sexual orientation.

This educational research has theoretical, quantitative, and qualitative components. To contribute to existing critical and liberative theories, two new models are proposed, one situating these theories relative to one another within the broader classification of identity-based theories, and another that provides example of the application of these theories to engineering systems. In a quantitative study, the disproportionately low outcomes of marginalized undergraduate students studying engineering at a highly selective public university are examined. Qualitative analyses of multiply marginalized students at this university determine some of the mechanisms through which these outcomes are occurring.

Societal structures, such as sexism, racism, and capitalism, have filtering effects that impact the opportunities available to individuals with marginalized identities throughout their lives. In order to correct inequities in engineering education, the role of current educational systems in the perpetuation of systems of oppression must be addressed. As incremental interventions fail to address the roots of these problems, they cannot remove the obstacles facing marginalized students. The true solution lies in the collective liberation of all marginalized people from oppressive social structures.

This work thus examines the role engineering education can and must play in the liberation of humanity from structural oppression.

PART A: Thermomechanical Experiments and Modeling of Shape Memory Alloy Tension Springs

CHAPTER I

Introduction to Shape Memory Alloy (SMA) Springs

1.1 Introduction to Shape Memory Alloys

This part of the thesis is concerned with the thermomechanical behavior of shape memory alloy helical springs. Shape memory alloys (SMA) are a primary item on a growing list of so-called "smart" materials that are rapidly gaining popularity in many areas of technical innovation [1]. The material, which consists of roughly equal parts nickel and titanium, along with optional additives, exhibits a change in stiffness based on both its temperature and its current stress state [1, 2]. The change in structural behavior is caused by a reorientation of the crystallographic substructure at the atomistic scale [2, 3]. SMAs exhibit two unique phenomena resulting from temperature-dependent martensitic phase transformations: pseudoelasticity and the shape memory effect [1, 2]. These, along with several other distinguishing features of SMAs, are shown in Figure 1.1 and briefly discussed in the following subsections. For more detailed information than is provided in this introduction, Dimitris C. Lagoudas's book *Shape Memory Alloys* [2] and Ashwin Rao, A.R. Srinivasa, and J.N. Reddy's book *Design of Shape Memory Alloy (SMA) Actuators* [1] are excellent resources. For more information on the materials science of phase transformation, I suggest *Microstructure of Martensite: Why It Forms and How It Gives Rise to the Shape-Memory Effect* by Kaushik Bhattacharya [3].

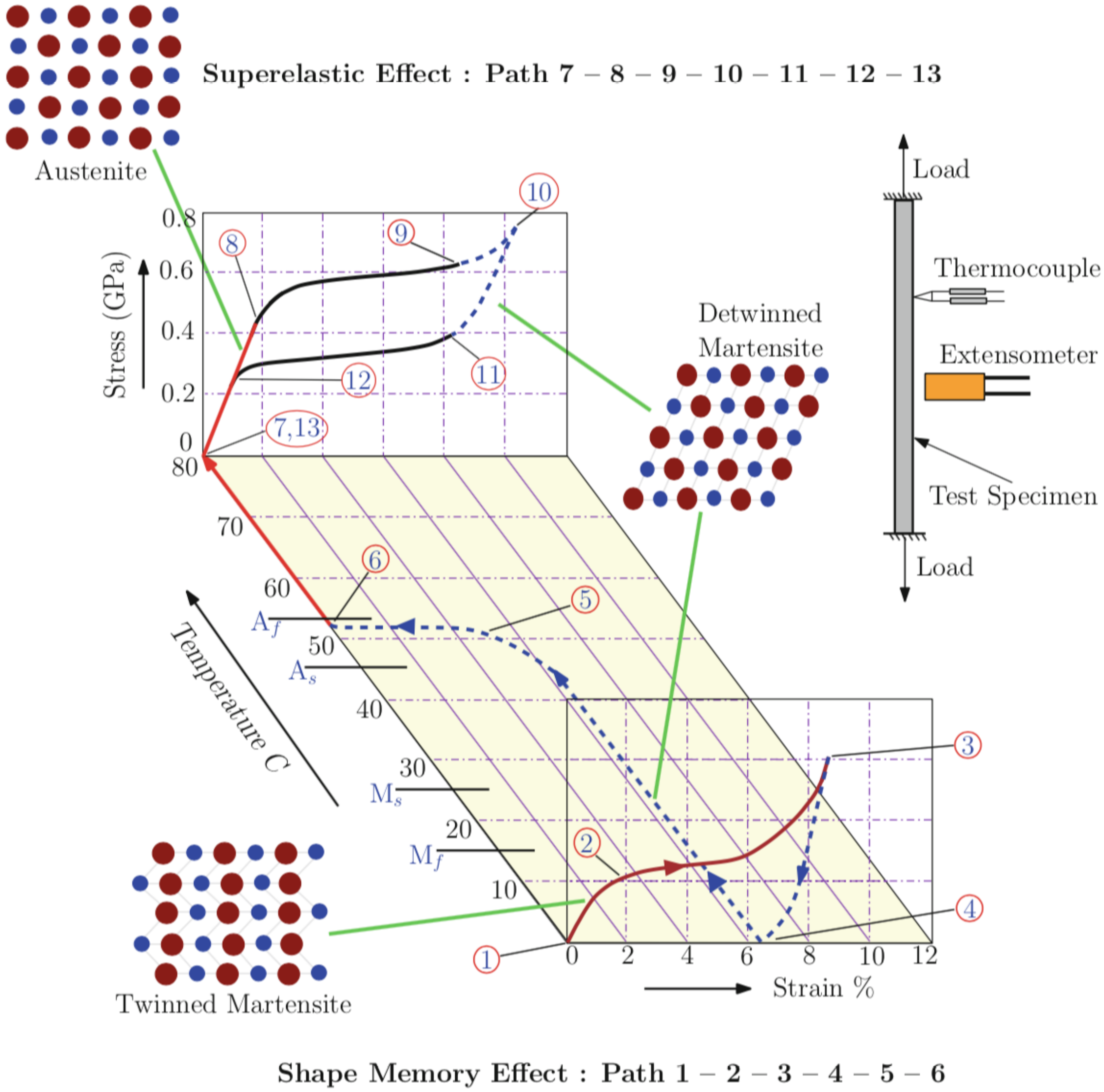


Figure 1.1: Pseudoelastic (stages 7-13) and shape memory (stages 1-6) behavior of an SMA wire (taken from [1], which was adapted from [4]).

1.1.1 Pseudoelasticity

Above its austenitic transition temperature, an SMA material exists in its austenitic phase. Austenite has a cubic crystal structure [1]. In this orientation, the material is pseudoelastic and recovers all deformation (up to approximately eight percent strain) when an applied force is released [1, 2] (see stages 7-13 in Figure 1.1). However, a hysteresis is present in the associated stress-strain curve, as the material transforms to a monoclinic stress-induced martensite (stages 8-9) at a higher level of stress than that upon which it transforms back to austenite during unloading (stages 11-12). This quality renders the material very effective for damping applications [1, 5–7]. In this thesis, the material tested has an austenitic transformation temperature of 90°C [8], so it must be significantly heated from room temperature in order to exhibit pseudoelastic behavior.

1.1.2 The Shape Memory Effect

Below its austenitic transformation temperature, SMA material exists in a martensitic phase [1, 2]. The atomistic orientation within martensite can be either monoclinic, orthorhombic, or tetragonal. The material can reorient between up to 24 different martensitic orientations (called "variants") via shear lattice distortion; this is referred to as a martensitic transformation. When a SMA material exists in an unloaded state below its austenitic reference temperature, its specific arrangement of a particular combination of variants is self-accommodated (stage 1 in Figure 1.1). This is called "twinned" martensite. Upon reaching a critical stress during mechanical loading (stage 2), however, the microstructure reorients to an arrangement in which a single variant is dominant, called "detwinned" martensite (stage 3). From twinned or detwinned martensite, the material maintains most of its deformation upon unloading (stage 4). Once the material is heated to austenite, however, it returns to its original configuration (stages 4-6).

This process constitutes the shape memory effect (also called the one-way memory effect), which is illustrated on a SMA spring in Figure 1.2. λ, as will be discussed in Section 2.3, is a dimensionless parameter defining the length of the spring relative to its unloaded austenitic reference configuration, at which $\lambda = 1$. At stage 1, the spring begins unloaded and in martensite (at a temperature below the austenitic transformation temperature). A load is applied between stages 1 and 2, mechanically

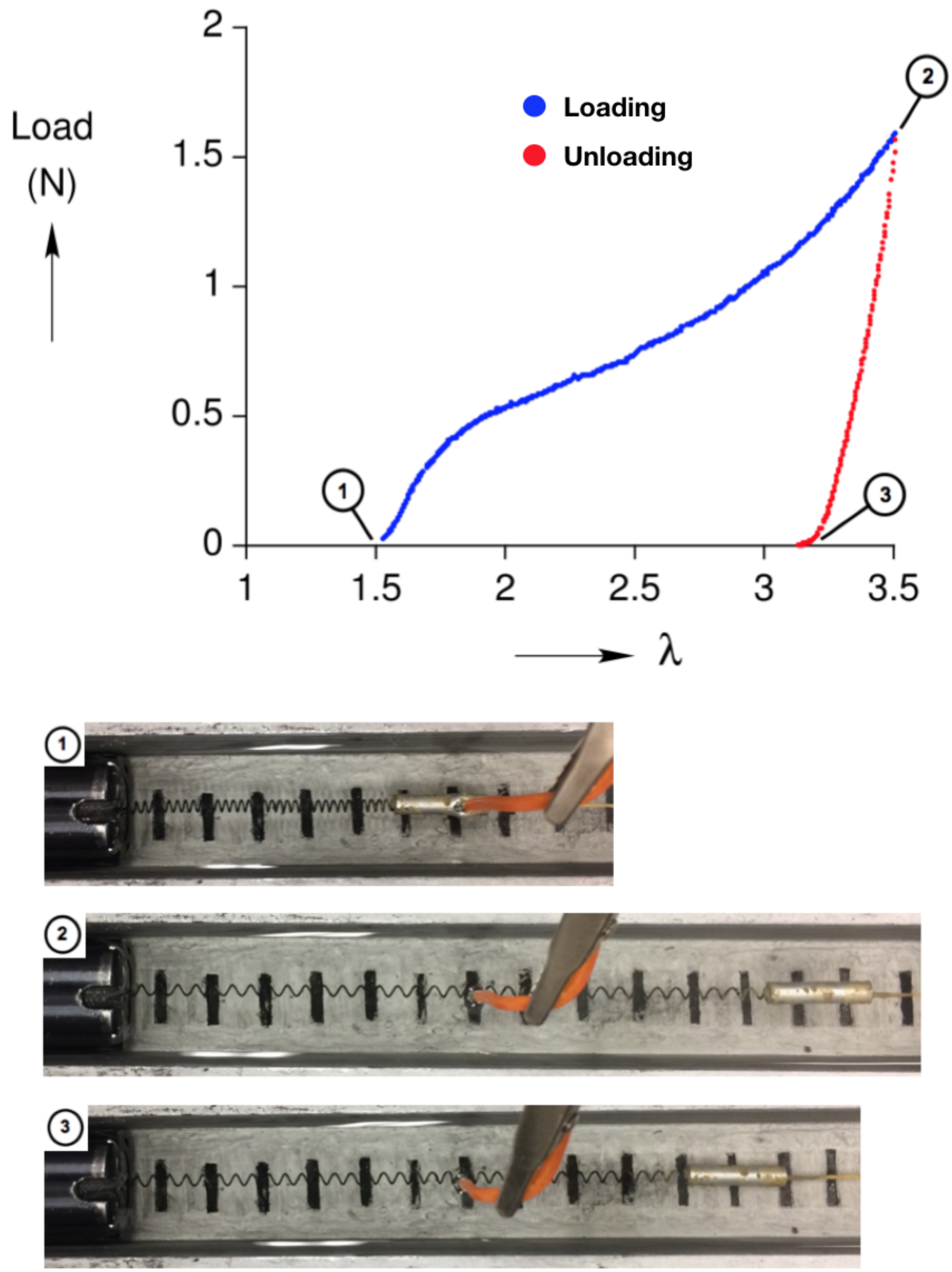


Figure 1.2: Example martensitic material response under isothermal loading and unloading.

deforming the spring to the state shown in Stage 2. At a load of approximately .5 N, the material point experiencing the highest stress begins to detwin, which is followed by the "martensitic plateau," during which the remainder of the material undergoes detwinning [2]. Between stages 2 and 3, the spring is mechanically unloaded, imperfectly retaining its deformation, as shown in stage 3. Heating the spring to a temperature above its austenitic transformation temperature will cause it to return to its close-packed reference configuration with $\lambda = 1$.

Many applications have taken advantage of the shape memory effect in SMA straight wires due to its stroke, the change in length of the wire as it undergoes thermal phase transformation [2, 9] (see Section 1.2.1). Under tension, SMA straight wires can recover a few percent elongation, either isothermally or through changes in temperature, which have enabled numerous applications as resilient structural elements or as thermal actuators. General Motors, for example, used a length of SMA wire to open a vent in the trunk of the 2014 Corvette [10]. Other examples of SMA wire actuators applied in civil, aerospace, and biomedical applications are detailed in [11–16].

1.1.3 Shape-Setting

In Section 1.1.2, it was explained that the SMA spring returned to its austenite reference configuration when heated. The shape to which it returns is that which it "remembers" from a prior process called shape-setting or heat-treating, in which the material is constrained in the desired position and subjected to high temperatures for long periods of time [1, 17, 18]. The particular parameters of heat treatment can vary, and ongoing research is investigating the effects of changes to the shape-setting process [19–23]. For more information on shape-setting SMA springs in particular, reference [1, 24–31].

1.1.4 Two-Way Memory Effect

Note that in our example of the shape memory effect on an SMA spring in Figure 1.2, the spring did not start in its reference configuration in stage 1. This is due to what is called the "two-way memory effect"; this spring remembers not only its austenite reference state, but also a secondary martensitic state [2]. When the spring in our example cools from its unloaded austenitic reference state, it elongates under no mechanical load. It is this elongated state that is shown in stage 1. The cause of the two-way shape memory effect is attributed to thermal cycling [1, 2], which is discussed in the next subsection, and ongoing research seeks to better explain and control the amount of two-way effect occurring in SMAs [32].

1.1.5 Cycling Effects

Through repetitive thermal actuation, SMAs undergo the process of "training," sometimes also called "shakedown." Previous research has begun to document the process of shakedown on SMA springs [28, 33–35]. Typical cycling behavior gradually decreases the material stiffness until it converges to a state of stable behavior [1, 2, 36]. This "training" process is completed before SMA wires or springs are utilized as actuators in order to ensure predictable behavior.

1.1.6 R-phase

As an SMA material in its austenite state cools to martensite, it sometimes passes through an intermediate crystallographic orientation called "R-phase" [2]. The crystal microstructure of R-phase is rhombohedral. The existence of R-phase is not universal in SMAs; it typically is suppressed by heat treatments at high temperatures [2, 20, 37]. It also is dependent on the particular composition of the SMA material [2, 37]. Ongoing research seeks to determine the conditions under which R-phase appears in SMA thermomechanial response [20, 38–41].

1.2 Introduction to SMA Springs

SMA wires in helical form provide enhanced kinematics that can be exploited in applications requiring large deformations but relatively low force [1, 31, 42]. The helical geometry provides significantly increased physical deformation upon temperature- or stress-induced transformation as compared to a straight wire; this makes SMA springs particularly useful as actuators [1, 2, 26, 31, 43]. The flexibility of the spring configuration also provides valuable tolerance forgiveness. The springs are produced by shape-setting SMA wires in the heat-treating process described in Section 1.1.3. More information on shape-setting SMA springs and experimental results on SMA springs shape-set in-house can be found in [20, 23–31].

1.2.1 Applications of SMA Springs

A large variety of industries have already demonstrated interest in SMA springs for their actuation ability. These include applications within the fields of:

- *Aerospace engineering:* vibration-damping airfoils [44, 45] and morphing airfoils [46, 47]
- *Mechanical engineering:* a gas foil bearing [48] and an electric piston [49]
- *Biomedical engineering:* a birth control method [50], a neurosurgical intracranial robot [51], an active catheter [31], a surgical gripper [52], a gut microbial capsule [53], and an artificial muscle [54]
- *Optics:* a deformable lens [55]
- *Energy harvesting:* from wind energy [56] and from thermal energy from fluids [57, 58]

1.2.2 Testing and Modeling of SMA Springs

The helical configuration of an SMA spring results in a multi-axial state of stress that is far more complex than that of a straight wire [33, 34]. Many efforts have already been made to document the thermomechanical behavior of SMA tension springs and develop numerical models that reflect the experimental results [9, 19, 20, 22, 24, 26, 28, 31–35, 38, 39, 42, 58–67]. A complete and thorough understanding of the stress-strain-temperature space for SMA spring actuators over the course of their lifetime of use, however, does not yet exist. This thesis seeks to build on existing work specifically by performing experiments with small increments of load and temperature and modeling the experimental data using both existing and proposed modeling techniques. This will enable further expansion of applications of helical SMA actuators. As such, the objective of this work is to comprehensively model the thermomechanical behavior of SMA springs, both in their virgin state and during cyclic actuation.

CHAPTER II

Experimental Design

2.1 Introduction

In this chapter, each section focuses on a different experimental setup for the testing of shape memory alloy (SMA) springs. The sections are arranged in the chronological order in which the experiments were designed and constructed, and each section documents what that particular setup is lacking that is addressed in the subsequent setup. The three experimental setups descibed are: 1) horizontal SMA spring mounting with actuation via joule heating (Section 2.2), 2) horizontal SMA spring mounting with actuation via convective heating (Section 2.3), and 3) vertical SMA spring mounting with actuation via convective heating (Section 2.4). Over the course of the entire narrative describing these experimental setups, more precise and controllable data is able to be achieved within the three-dimensional force-displacement-temperature space.

2.2 Horizontal Mounting and Joule Heating

Experiments on shape memory alloy (SMA) springs were first performed using a force-controlled experimental setup designed by former students of Professor Diann Brei in the Mechanical Engineering department at the University of Michigan [24, 68].

The mechanical response of the spring is recorded as measured force versus spring displacement while the spring undergoes phase transformations induced via joule heating. A spring is pinned into two electrically-conductive collets, thus achieving fixed-fixed boundary conditions. A photograph of a spring sample mounted in this experimental apparatus is provided in Figure 2.1.

The mechanical response of commercially-available Flexinol® nickel-titanium springs manufactured by Dynalloy [8] was characterized by the cyclic heat-cool characterization method described by Czarnocki [24]. The spring begins in an unloaded, austenitic state. The load is incrementally increased, and, at each constant load value, the spring is allowed to cool naturally to room temperature, thus transforming to martensite, before being heated again to austenite. This procedure is repeated until the martensitic response completes the linear plateau and begins to increase in slope, producing the full martensitic response curve. An example of the material response is shown in Figure 2.2. The point of maximum strain at each load value, which occurs when the spring is fully transformed to its martensitic state, is indicated in blue, and the point of minimum strain, in austenite, is shown in red. Thus, the resulting red curve in Figure 2.2 is the austenitic loading curve of the spring, while the blue curve shows martensitic loading. This experimental procedure is able to accurately capture the actuation behavior of the SMA spring.

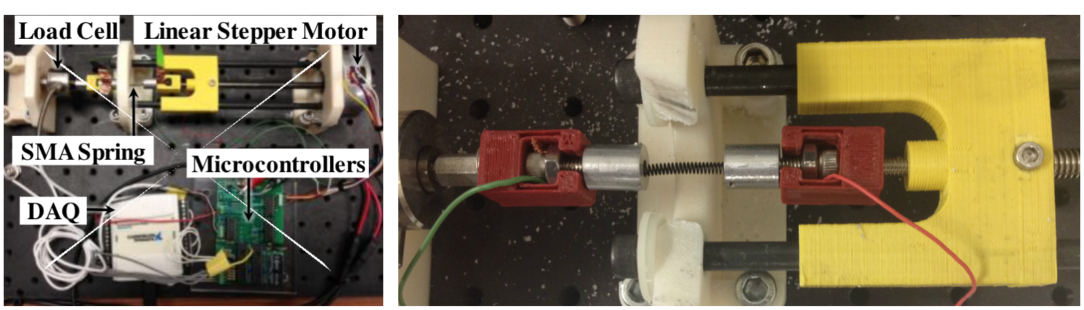


Figure 2.1: Horizontal setup with joule heating, constructed by members of Prof. Brei's laboratory and used in [24, 68]

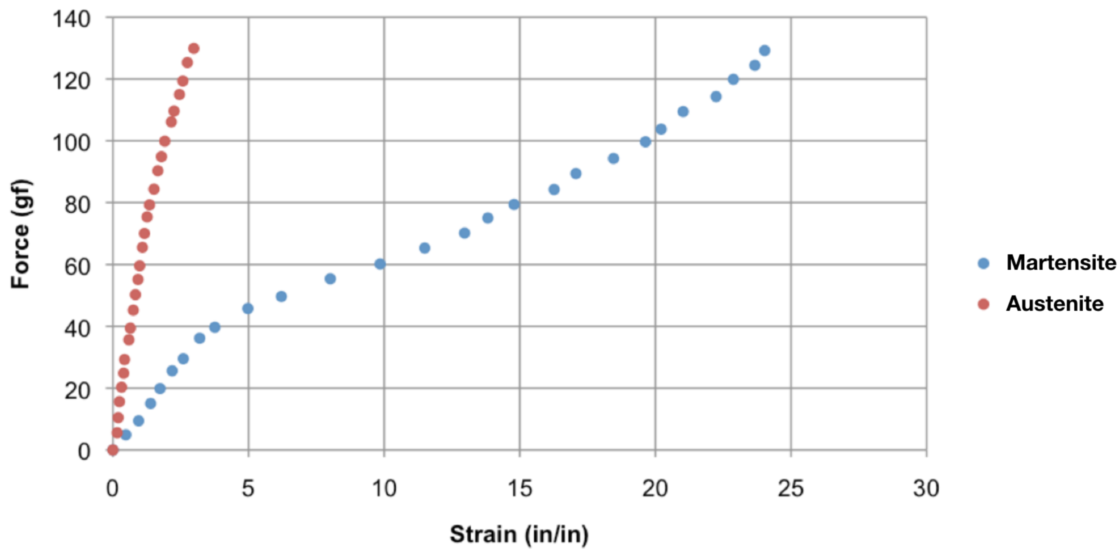


Figure 2.2: SMA material response.

2.2.1 SMA Spring Actuator Design Tool

The Dynalloy spring results were compared to those of springs heat-treated, or shape-set, here at the University of Michigan by members of Prof. Brei's laboratory [24]. This data was then added to the design tool used to design springs for use as actuation devices. By extracting and plotting the performance metrics from experimental results such as that shown in Figure 2.2, the design tool can be used to size the SMA spring required to meet actuation needs for various applications. This updated design tool is shown in Figure 2.3.

In the design tool shown in Figure 2.3, percent strain (shown in red) and non-dimensionalized force (shown in green) are plotted against the spring index of the tested sample. The percent strain and final force F_p values of each sample are extracted from the endpoint of the martensitic plateau. Strains are calculated relative to the close-packed configuration of the spring. The force value is non-dimensionalized

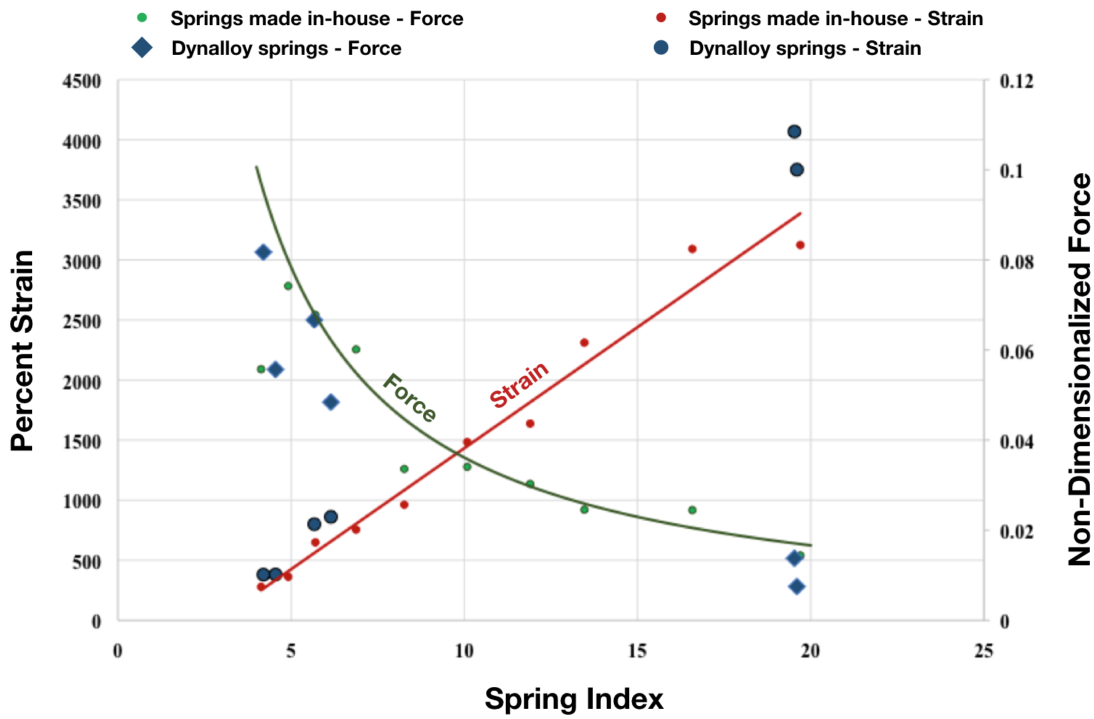


Figure 2.3: Updated SMA actuator design tool, compiled by Dr. Jonathon Luntz.

relative to the characteristic force of the spring

$$F = \frac{F_p}{F_c} \tag{2.1}$$

where the characteristic force F_c is the maximum tensile force of the wire. This is given by

$$F_c = \sigma_c \frac{\pi d^2}{4} \tag{2.2}$$

where σ_c is the tensile stress of the material. The spring index of each sample is calculated by

$$I = \frac{D}{d} \tag{2.3}$$

where D is the centerline diameter of the helical actuator and d is the diameter of the SMA wire. Thus, small spring indices, on the order of four to eight, indicate stiffer springs, whereas large spring indices, on the order of fourteen to twenty, indicate flimsier springs.

The non-dimensionalized results shown in Figure 2.3 constitute a two-step design tool that exposes the trade-off that exists between stroke and force in the design of helical actuators [24]. The kinematic step is first employed to determine the appropriate spring index of the actuator based on the required stroke and physical constraints. Then, in the kineto-static step, the spring index is input to determine the resulting non-dimensionalized force. The spring parameters d and D can then be determined from Equations 2.2 and 2.3, respectively. For more detail on the helical actuator design tool, see its original publication by Czarnocki [24].

The contribution of this work is to add commercially-available Dynalloy springs [8] to the design tool, which previously only included in-house made springs. In Figure 2.3, the large data points (blue circles and diamonds) are the Dynalloy samples, and the small data points (green and red circles) comprised the previous model of SMA springs shape-set in-house [24]. Dynalloy springs are found to have relatively similar force values to those made in-house, but the former exhibit slightly larger strains.

2.2.2 Setup Disadvantages

While this experimental setup is useful for the determination of mechanical response, its limitations in controllable parameters are problematic for a variety of experiments. Specifically, this apparatus provides the stress-strain response in the presumed austenite and martensite states but neglects to record the state of temperature within the material. Thus, this setup is not capable of characterizing the three-dimensional stress-strain-temperature response of SMA springs.

2.3 Horizontal Mounting and Convective Heating

A new experimental apparatus is designed and constructed that has the ability to determine the thermomechanical response of springs by controlling either force or displacement while also controlling and measuring temperature. This versatile setup allows for the full characterization of a spring's actuation abilities. This experimental apparatus consists of a long, thin aluminum channel containing the SMA spring sample submerged in silicone oil. The channel is comprised of aluminum alloy 6063. This was selected due to the workability of the material as well as its ability to withstand high temperatures. The thirty-inch length of the channel allows stretch ratios in excess of 20 in/in; in the reminder of the results presented within this thesis, the stretch ratio will serve as the strain-related variable, and it is defined as follows:

$$\lambda = \frac{L_{current}}{L_{reference}} \tag{2.4}$$

where L is the length of the spring.

The silicone oil that fills the channel is Dow Corning 200 fluid, with a viscosity of 10 CST [69], which was selected due to availability. One end of the spring is fixed in place on one end of the channel using an ER collet, while a collet on the free end of the spring attaches to a length of Kevlar thread. A pulley at the far end of the channel changes the direction of the Kevlar thread and feeds it into a Futek LRF400 axial load cell [70], which is attached to the cross head of an Instron electromechanical testing machine. The maximum load capacity of the load cell is 10 N. The Instron can be configured to apply either load or displacement control during testing. The Kevlar thread is assumed to be inextensible, so the axial position of the free end of the spring is offset from the position of the Instron cross head. Output signals from the thermocouples, the Instron, and the load cell are all read by a National Instruments DAQ and analyzed in LabVIEW. This setup is depicted schematically in Figure 2.4, and a photograph is shown in Figure 2.5. Note that the photograph shows strip heaters rather than cartridge heaters. A sample image of a spring mounted in the apparatus is shown in Figure 2.6 (the black marks in the channel are one centimeter apart for scale).

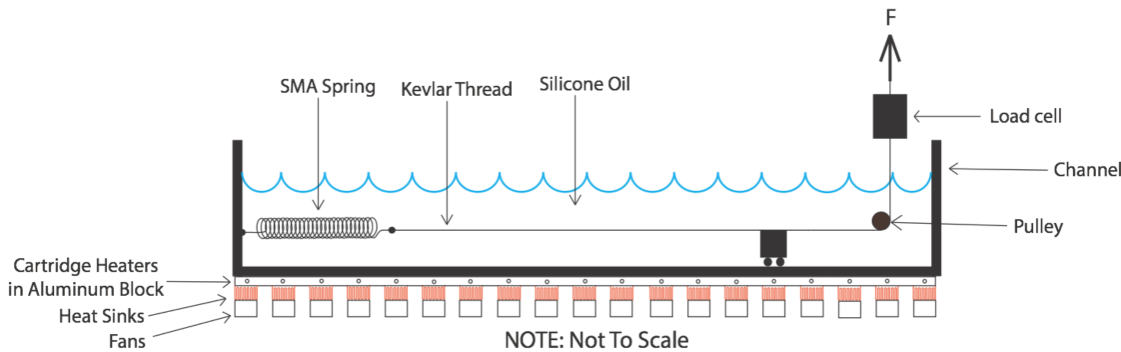


Figure 2.4: Schematic drawing of experimental apparatus with horizontal mounting and convective heating.

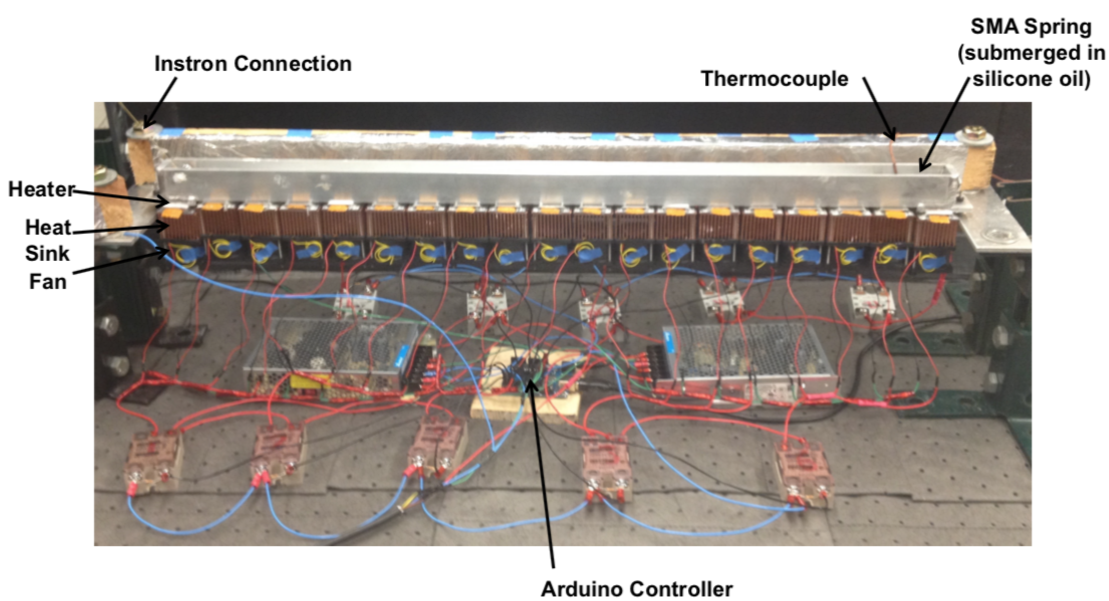


Figure 2.5: Thermomechanical experimental setup.

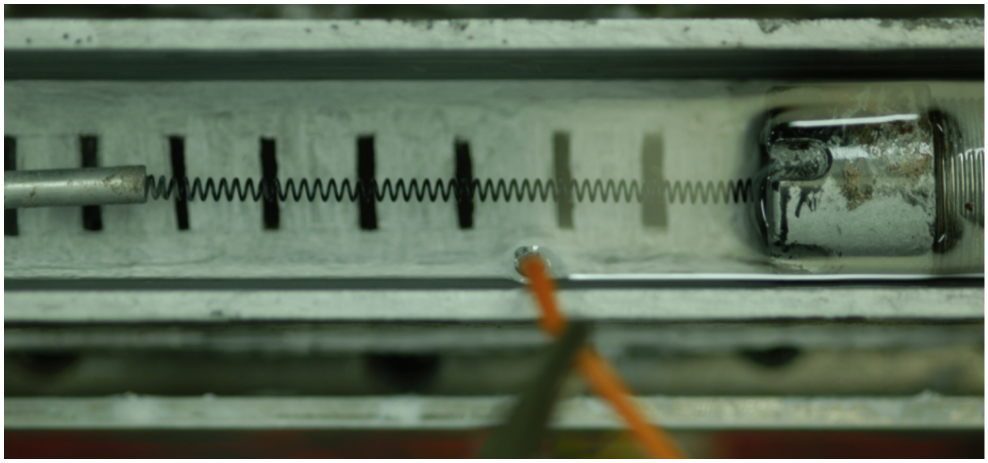


Figure 2.6: Mounted SMA spring.

2.3.1 Heat Transfer

Figure 2.7 shows a diagram of the electrical circuit that powers the heating and cooling system. The geometrical measurements of this apparatus are shown in Table 2.1. In the design, using the maximum number of 19 strip heaters and heat sinks would be optimal, because it would ensure the fastest possible heating and cooling rates for the apparatus. The maximum temperature that the spring should achieve is 120°C, so the power requirements to maintain that temperature in the spring are calculated using a layer-by-layer analysis. The results are used to verify that steady

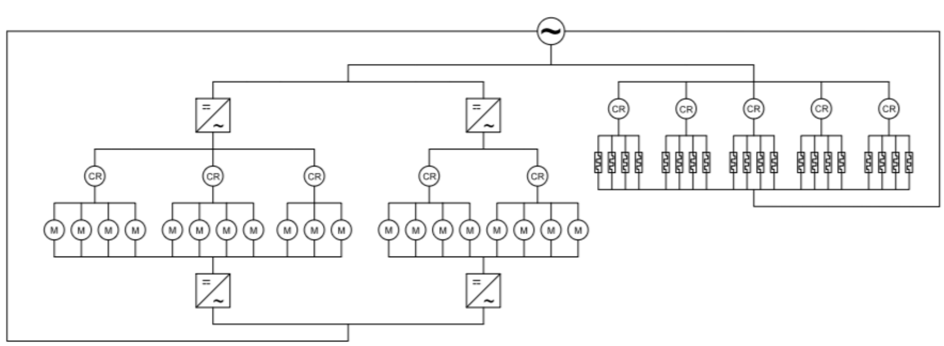


Figure 2.7: Heating and cooling system circuitry diagram (M-fan and CR-solid state relay).

Table 2.1: Geometrical properties of experimental apparatus components.

Variable	Description	Value
t_{al}	Thickness of aluminum	.0016 m
A_{al}	Bottom surface area of aluminum	.0097 m^2
t_{oil}	Thickness of oil	.0111 m
A_{oil}	Exposed surface area of oil	.0072 m^2
n	Number of strip heaters / heat sinks	19
n_{fin}	Number of fins on a heat sink	99
l_{fin}	Length of heat sink fin	.025 m
A_{fin}	Cross-sectional area of heat sink fin	.000002 m^2
t_{hs}	Thickness of base of heat sink	.005 m
A_{hs}	Exposed area of heat sink	.0193 m^2
$A_{hs,b}$	Area of base of heat sink	.00131 m^2
t_{sh}	Thickness of strip heater enclosure	.0015 m
$A_{sh,c}$	Area of channel covered by a strip heater	.00044 m^2
A_{sh}	Area of strip heater	.001 m^2

state is attainable in this design. In general, the problem is considered to be one-dimensional, but some liberties are taken to take into account some aspects of the geometry without considering two-dimensional heat transfer.

Heat is generated in the strip heaters, from where it travels out through the upper and lower aluminum encasings. (The strip heaters were later replaced with more powerful cartridge heaters; thus, this analysis is conservative.) The heat that travels down then goes into the heat sinks, and, from there, it escapes into the surrounding air via convection. The heat that travels through the upper enclosures then passes through the thickness of the aluminum channel. From there, it splits between heating the contents of the channel and exiting the apparatus through the exposed bottom of the channel between the strip heaters. (While it is recognized that the path through the bottom of the channel first requires heating across the length of the channel, and thus constitutes two-dimensional heat flow, this approximation is desirable as compared to ignoring the effects of these losses.) After conduction through the bottom of the channel, the vast majority of the heat is only travelling upwards through the oil, but a small fraction of it must travel across the wire diameter of the spring on its way through the oil. The thermal circuit that is equivalent to the entire apparatus is shown in Figure 2.8. The results of the steady-state treat transfer calculations are shown in Table 2.2.

To calculate the power requirement, an energy balance within the apparatus is

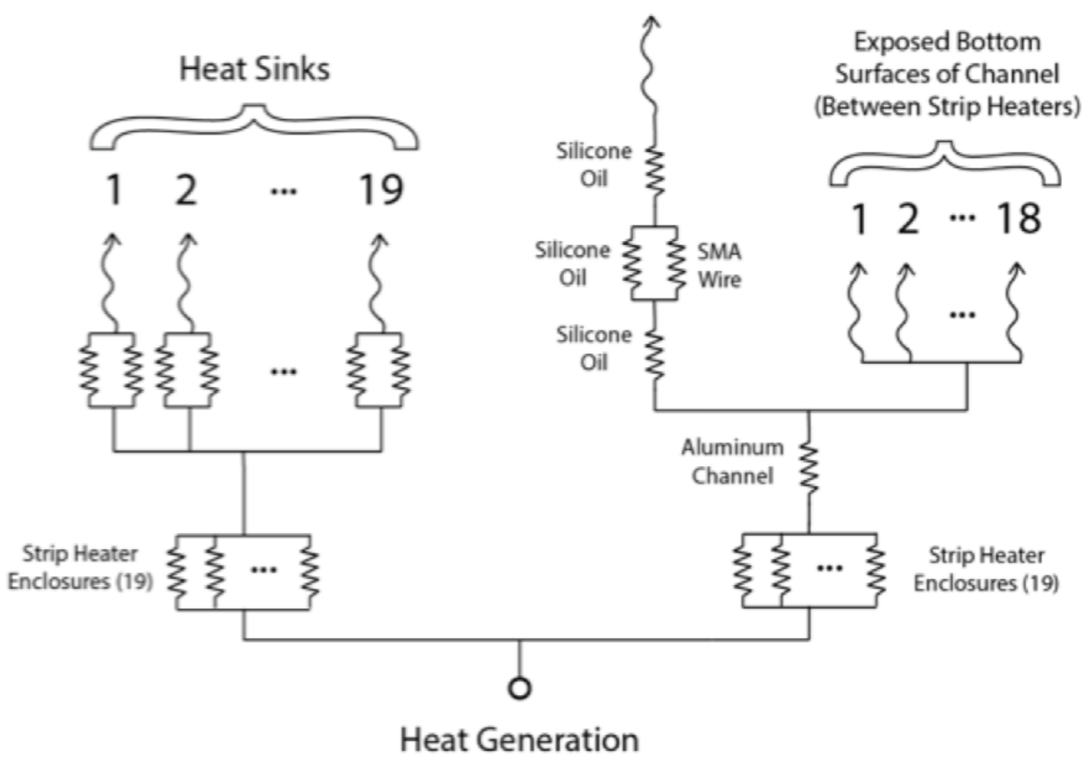


Figure 2.8: Equivalent thermal circuit for horizontal mounting and convective heating experimental apparatus.

Table 2.2: Steady-state heat transfer results.

Description	Value
Oil surface temperature	97°C
Spring temperature	120°C
Aluminum/oil contact surface temperature	152°C
Heat transfer rate through channel	4.2 W
Heat transfer rate through spring	.6 W
Heat transfer rate through oil	3.5 W
Heat transfer rate through strip heaters	5.4 W
Strip heater temperature	190°C
Heat transfer rate through heat sinks	24.2 W

considered. The required power is thus the sum of the losses through the upper and lower portions of the apparatus: $q_{req} = 5.4\ W + 24.2\ W = 29.6\ W$. This can easily be provided with 19 20-Watt strip heaters, with an excess power of 350.4 W beyond what is needed to maintain steady state. The strip heaters can thus easily provide a sufficient amount of power to maintain a constant spring temperature of 120°C.

Upon construction, the 19 20-Watt strip heaters were replaced with 19 cartridge heaters providing 100 W of power each [71]. Therefore, the cartridge heaters far exceed the necessary power. A variable transformer was employed to limit the voltage supplied to the cartridge heaters and prevent overheating.

An Arduino-controlled electrical power system connected to cartridge heaters and high efficiency fans is located underneath the channel. The 19 Sunon 10.8 W fans, which each move approximately 30 cubic feet of air per minute [72], are directed downward, directing air away from the experimental apparatus through cooper heat sinks as shown in Figure 2.4. The heat sinks have two-dimensional fins to increase the rate of convection during active cooling. Two external tabletop fans are also wired into the system. To control the temperature of the oil along the channel's length, which is read by a series of Omega thermocouples, the operator adjusts the pulse width modulation to the heaters and fans via ten solid state relays and the Arduino Uno controller [73].

To quantify the actual steady-state heating of the experimental apparatus, the model shown in Figure 2.9 is developed from the center thermocouple response. The first-order steady-state heat transfer equation is applied to each of the four power values that reached close to steady-state.

$$T(t) = K_p \Delta P (1 - e^{(-\frac{t-L}{\tau})}) - T_i \tag{2.5}$$

where P is the power input. Best-fit parameters are determined for the static process

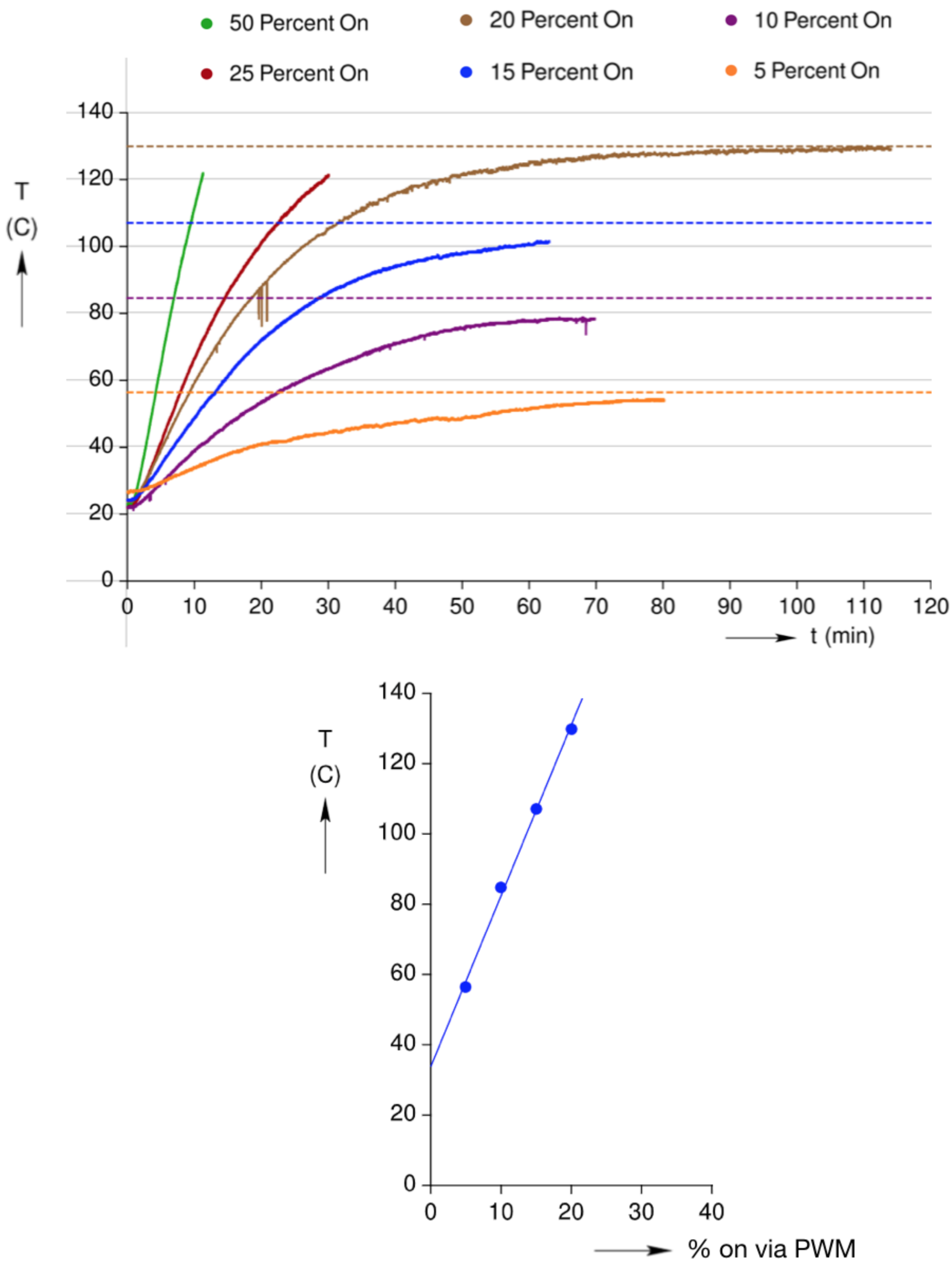


Figure 2.9: Steady-state heating model of channel center using pulse width modulation.

gain K_p, the apparent time delay L, and the apparent time constant τ. The steady-state temperature T_∞ can then be determined from the limit as $t \to \infty$. The overall static process gain of the system is then given by the equation

$$K_p = \frac{\Delta T}{\Delta P} \tag{2.6}$$

From a linear fit of the four data points extracted from the steady-state model, the static process gain of the system is determined to be $K_p = 4.86$. From this model, it can be seen that the cartridge heaters will not need to be on more than twenty percent of the time in order to maintain a spring temperature of 120°C.

2.3.2 Setup Disadvantages

This experimental setup is able to produce remarkably clean data. Example isothermal results are shown in Figure 1.2 in Section 1.1.2. Load-controlled thermomechanical results are provided in Figure 2.10. However, there is a significant problem in regards to thermal uniformity. Using an infrared camera, we can see that the temperature gradient between the ends of the channel and the center during heating is extremely significant, as shown in Figure 2.11. Insulating the ends of the channel blocked some heat loss at the ends but did not even out the temperature distribution along the length of the channel. Attempts to use PID control to create an even temperature distribution were unsuccessful due to the delayed feedback instability. Manual control of the pulse width modulation of groups of heaters along the channel length improved the temperature distribution, but 10-15°C temperatures differences along its length remained (see Figure 2.12). A photograph of the experimental apparatus with the ends insulated set up in position with the Instron load frame in shown in Figure 2.13.

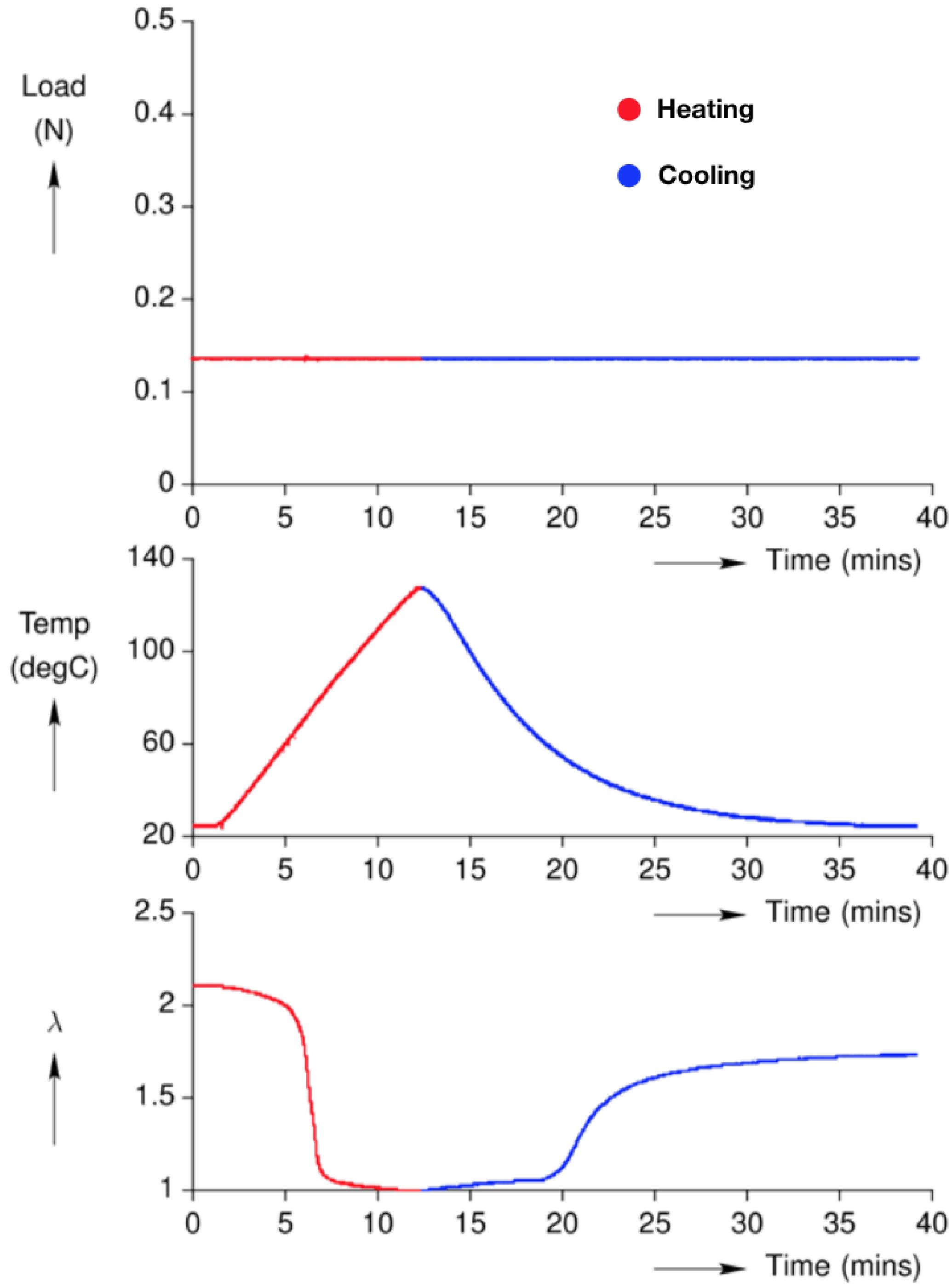


Figure 2.10: Example thermomechanical material response under constant loading conditions.

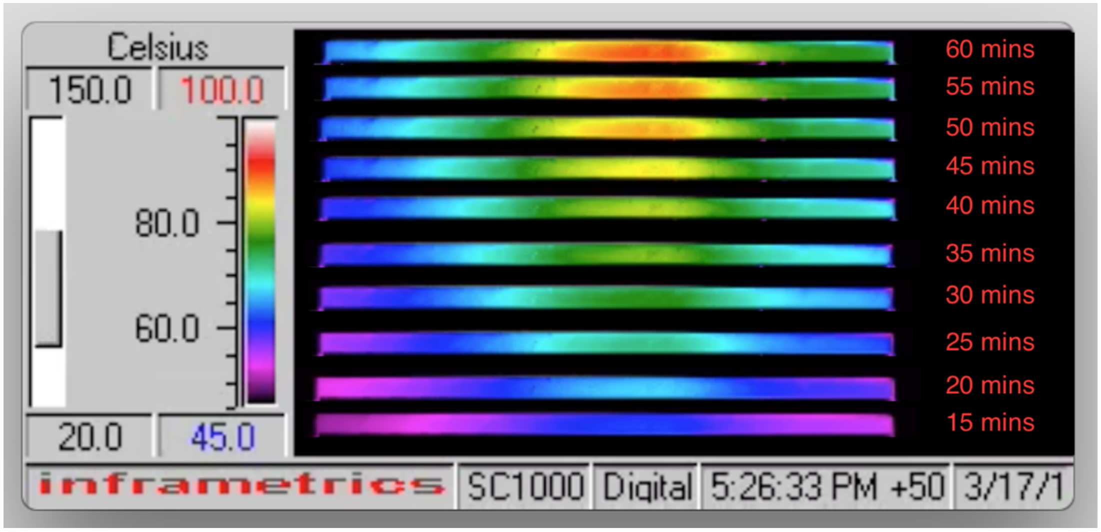


Figure 2.11: Temperature distribution along channel during heating.

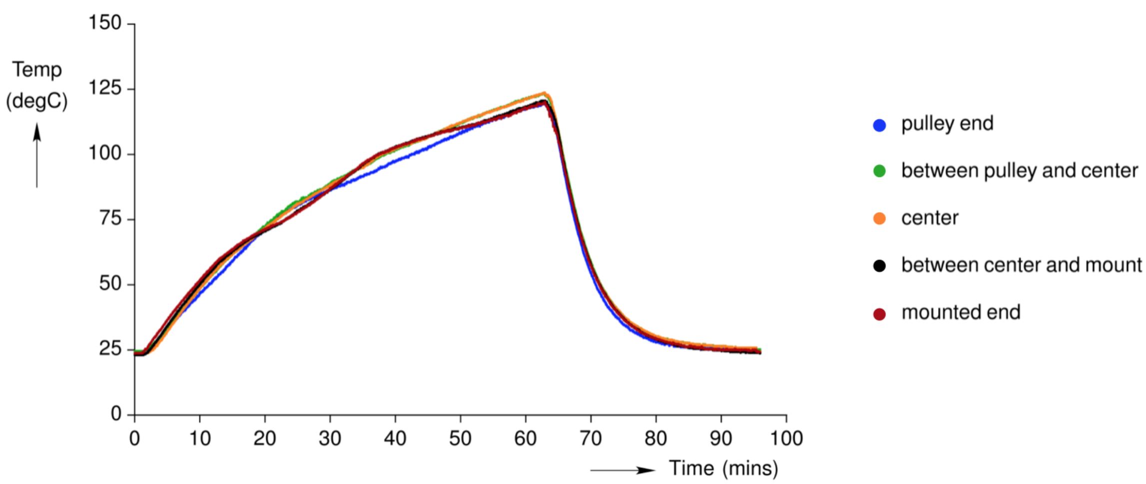


Figure 2.12: Temperature distribution along length of insulated channel during heating and cooling with manual control of pulse width modulation.

Figure 2.13: Insulated experimental setup shown in position.

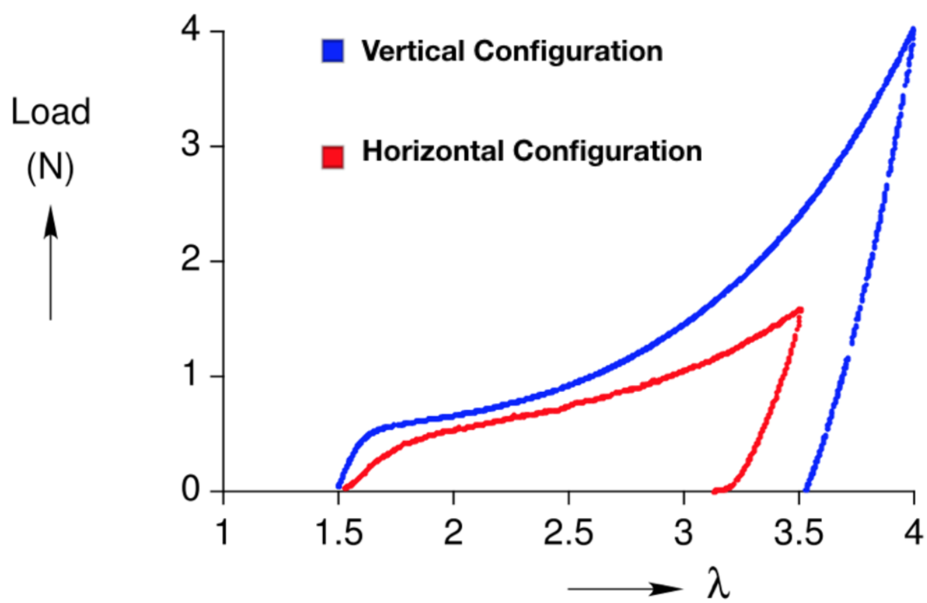


Figure 2.14: Martensitic isothermal responses at 30°C on a Dynalloy CS# 4608 spring sample using two experimental setups.

In addition to the lack of uniform temperature distribution across its length, there are further concerns regarding the pulley by which the force within the spring sample is redirected upward to the load cell and Instron frame. While efforts can be made to acquire or produce a pulley that is concentric and low in friction, comparisons with results using the experimental setup described in Section 2.4 suggest that imperfections in these qualities result in significant error within the load readings, as shown in Figure 2.14. These results imply that the pulley absorbs a significant amount of the load on the spring.

2.3.3 Plastic Deformation Testing

The helical geometry of an SMA spring provides a significantly increased physical deformation upon temperature-or stress-related transformation compared to a standard wire, which is part of what makes SMA springs particularly useful as actuators [1, 31, 42]. This increase in stroke can also make experimental characterization difficult, however, due to the geometry of the space required; a spring is capable to stretching out up to many times its original length. Therefore, the extended length of this channel is utilized to perform incremental loading experiments in both the austenitic and martensitic regimes. The purpose of these experiments is to determine at what stretch ratio the spring fails to recover its original configuration upon re-heating. This will occur due to plastic deformation when the incremented applied load induces local stresses in excess of the material's yield stress [74]. This testing procedure is not identified in literature but is useful for the purpose of determining what length for spring actuation is required for future experiments. In these experiments, I will aim to characterize the thermomechanical behavior of SMA springs without inducing plastic deformation.

Plastic deformation testing is performed using a Dynalloy CS# 4608 SMA spring with an advertised transformation temperature of 90°C [8]. The spring index is measured to be 5.00 and the wire diameter is .43 mm. The spring sample has 43 coils and is partially shaken-down prior to testing.

The austenitic reference length of the spring is determined by measuring the free length of the spring when resting on a flat surface and heated with a heat gun. Once the sample is mounted, the oil bath is heated until the thermocouple closest to the spring sample reads 120°C. The Instron cross head is jogged until the spring achieves its austenitic reference length. The load measured by the load cell at this point, .163 N, corresponds to zero load on the spring in austenite, and is subtracted for spring load calculations. The spring is then loaded and unloaded incrementally at a strain rate of one per minute while the temperature is held constant. Unloading first begins at a measured load of 1 N and then increments by 1 N with each re-loading to a maximum load of 10 N. Given perfect pseudoelasticity, the spring would be expected to recover its initial length upon each unloading [2], but the results in Figure 2.15 show that significant plastic stretch within the austenitic regime begins to occur at spring loads of approximately $4-5$ N. Thus, the spring begins to accrue irreversible

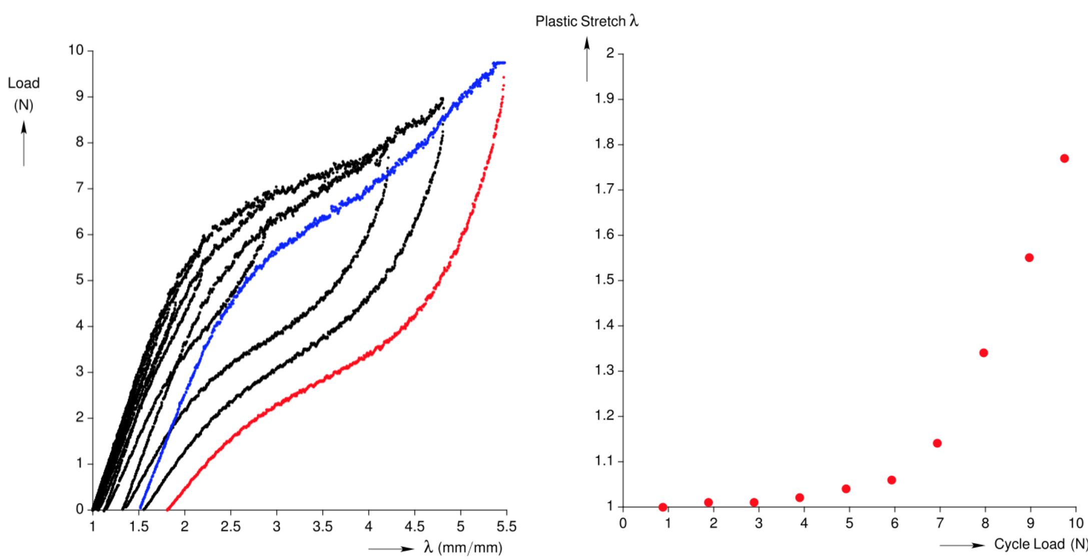


Figure 2.15: Irrecoverable stretch in the austenite phase during incremental loading.

damage in austenite when taken to stretch ratios of approximately 2.

For martensitic tests of incremental loading, isothermal tests are performed at room temperature. The oil bath is heated again to 120°C with no load applied to the spring. The oil bath is then cooled to room temperature. The stretch ratio of the spring increases to approximately $\lambda = 1.5$ during cooling due to the two-way effect of the SMA material (see Section 1.1.4). The spring is then loaded to a load cell measurement of 1 N (again at a strain rate of one per minute) and then unloaded. The oil bath is again heated to 120°C. This process is cycled as before, incrementally increasing the maximum load value by 1 N to a maximum load of 10 N. The results in Figure 2.16 show that significant plastic stretch within the martensitic regime begins to occur at loads of approximately 3 N. This corresponds to a stretch ratio of approximately 4.

Although the load readings may not be accurate in these experiments, the results demonstrate that irrecoverable damage in the form of plastic deformations occurs at relatively small values of stretch. Therefore, the extended length of this experimental setup, which allows a maximum spring length of approximately 540 mm, is not needed

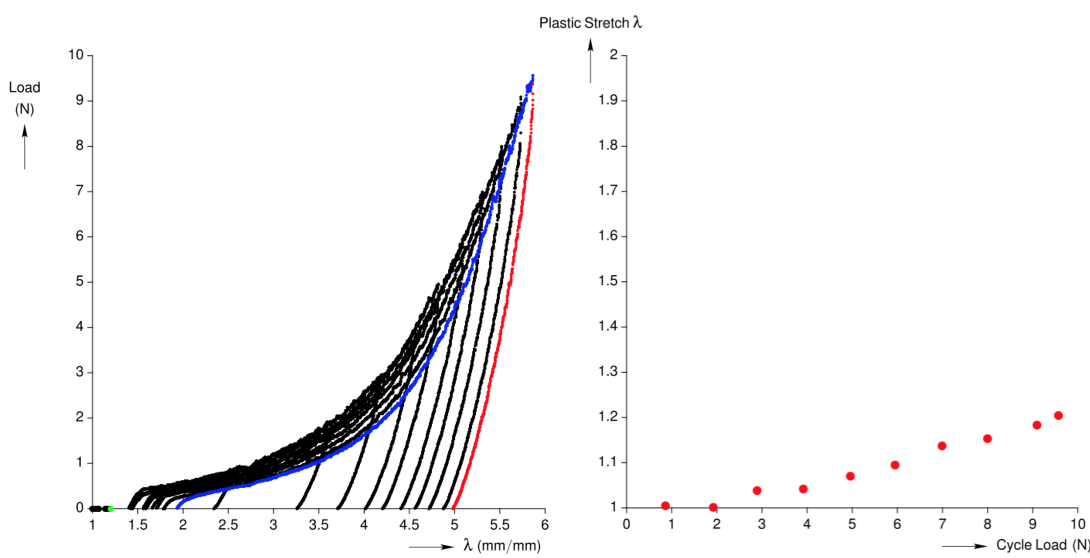


Figure 2.16: Irrecoverable stretch in martensite during incremental loading.

for future experiments. I instead pursue the setup described in Section 2.4.

2.3.4 Rotational Phenomenon

SMA springs exhibit a complex relationship between axial, bending, and torsional stresses that changes with thermal or mechanical loading [34]. A notable phenomenon is first observed during isothermal testing of shaken-down SMA springs using this experimental setup that demonstrates the changing relationship of these stresses as the spring is loaded and unloaded. Figure 2.17 shows still images taken from an isothermal test and the axial and rotational directions in which the spring moves between the different stages of the experiment. In the photographs, the spring sample is located to the right of the yellow collet (which is free to rotate), and the other end of the spring is fixed to the right end of the channel outside the view. The spring used is Dynalloy CS# 4609 with a measured spring index of 4.20 and a wire diameter of .38 mm. The spring contains 55 coils. This test was performed at room temperature.

In Figure 2.17, image 1 shows the initial configuration of the spring. As the spring is loaded, it is seen to rotate clockwise (from the perspective of the spring) between images 1 and 2. Between images 2 and 3, however, the spring rotates in the counter-clockwise direction, even as it continues to elongate. Then, as the spring is

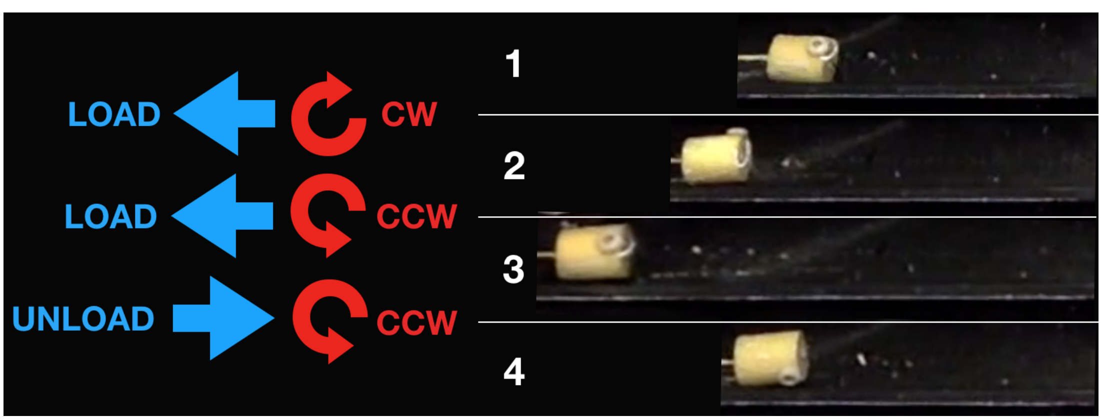


Figure 2.17: Rotational phenomenon occurring during isothermal testing of shaken-down springs.

unloaded, it continues to rotate in the counter-clockwise direction until it reaches its final unloaded state in image 4.

As will be seen throughout this thesis, this rotational phenomenon was observed to take place using a variety of experimental setups, spring geometries, and cycling histories, as long as the boundary conditions allowed one end of the spring to rotate. No discussion of this phenomenon could be located in the literature. As will be discussed, there is reason to believe that the change in direction of rotation is an effect of R-phase transformation within the SMA material and may be the result of a transformation-induced instability. This will be elaborated upon further throughout Chapters III and IV.

2.4 Vertical Mounting and Convective Heating

Experiments are performed using an Instron load frame and thermal chamber. The Instron is operated using the software program Partner, and the thermal chamber is actively cooled with liquid nitrogen. A spring mounted vertically inside the thermal chamber by threading the ends around set screws, setting a layer of high-temperature glue to hold the spring in place, and then clamping one end into a drill chuck or fixed collet located near the bottom of the thermal chamber. The other end is inserted into a collet and connected to the Futek LRF400 axial load cell (maximum load 10 N) [70] by a length of Kevlar thread, which is again assumed to be inextensible. Due to this inextensibility assumption, the spring displacement can be determined from the grip displacement via an offset. Omega thermocouples record the temperature of the spring at various points along its length [75]. Signals from Partner, the thermocouples, and the load cell are all read into LabVIEW. It is seen that the spring can achieve small stretch ratios without any significant variation in temperature along its length; the space in which the spring can safety expand is approximately 180 mm in length. The experimental setup is depicted schematically in Figure 2.18.

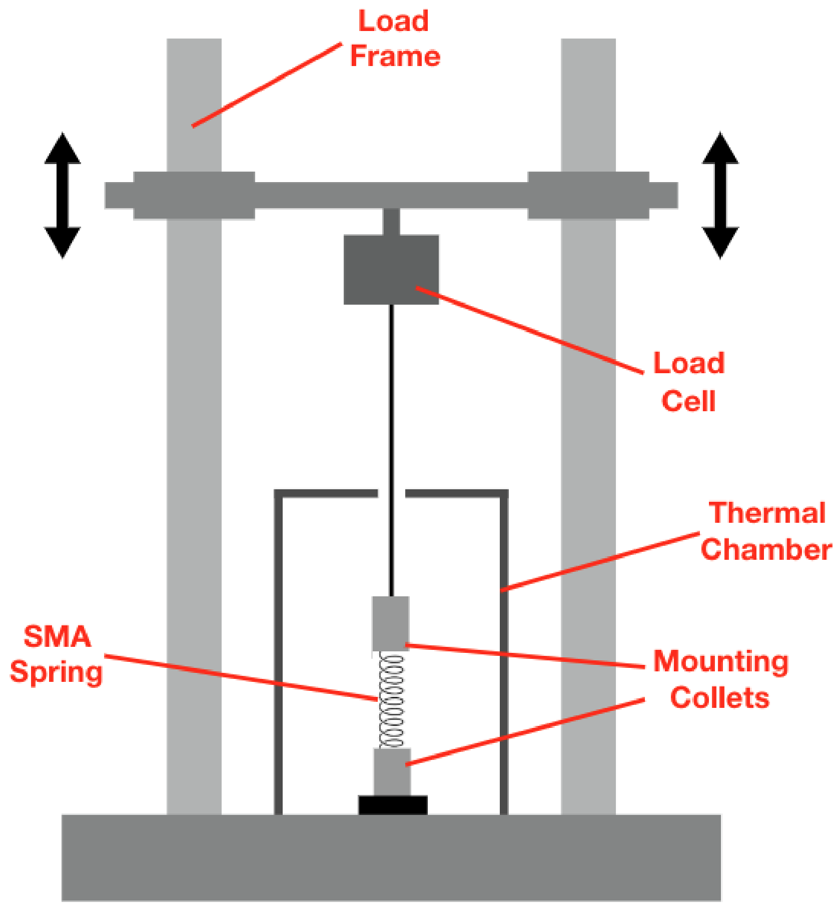


Figure 2.18: Experimental setup.

2.4.1 Determination of the Reference State

To achieve a more accurate approximation of the offset between the spring load and the load cell reading than described in Section 2.3, a new procedure is developed that is employed before every remaining test described in this thesis. After the sample is mounted, the thermal chamber is heated to 120°C. The Instron cross head is manually jogged upwards to put the spring under tension. Displacement controlled testing then slowly lowers the position of the cross head at a constant rate. The test is ended manually once the spring is visibly lax within the thermal chamber. An example of the resulting data, plotting the load cell reading against the position of the Instron cross head, is shown in Figure 2.19. In post-processing, best-fit linear approximations

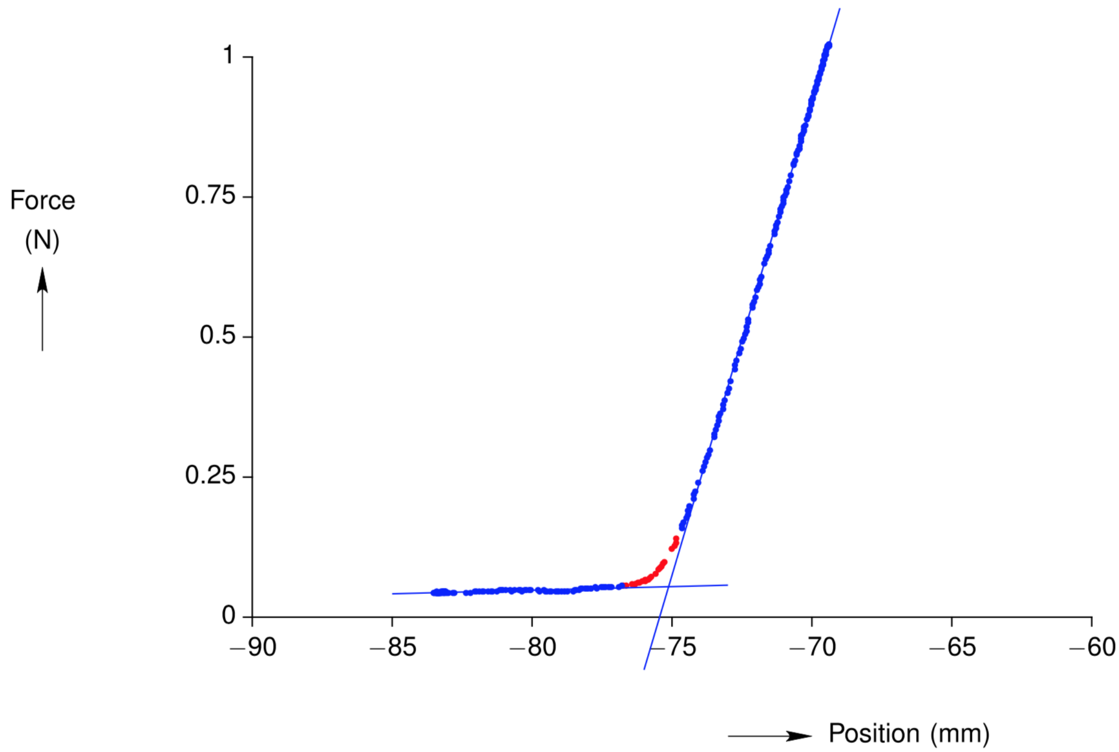


Figure 2.19: Example of experimental testing and postprocessing construction of load cell reading and Instron cross head position corresponding to the unloaded spring state (red points are not used for best-fit line constructions).

are fit to the ranges of data corresponding to the spring under tension and the spring hanging lax. The intersection point of the two lines is assumed to correspond to the unloaded state of the spring sample. Thus, in the example shown in Figure 2.19, the offsets from zero for the load and displacement are determined to be .054 N and -75.12 mm, respectively.

A repetition of this testing procedure at room temperature demonstrates that the difference between the load offsets in austenite and martensite is negligible (.054 N vs .095 N, respectively).

2.5 Conclusion

The experimental apparatus described in Section 2.3 is constructed in response to the inability of the previous setup (described in Section 2.2) to control the temperature of the spring. The extended length for large deformations available by the oil bath setup in Section 2.3 is found to be unnecessary due to the plastic deformation that is induced at relatively small stretch ratios (which was determined in Section 2.3.3). The experiments in Chapters III and IV are therefore performed using the simpler setup that was described in Section 2.4.

CHAPTER III

Isothermal Experiments and Modeling of SMA Springs

3.1 Introduction

Shape memory alloy (SMA) springs are commonly used as actuators in a wide variety of applications [1, 2, 26, 31, 43]. The first critical step of actuator design is to understand the stretch response of the spring to an applied load. This response is temperature dependent, resulting in either pseudoelasticity (see Section 1.1.1), when the material is above the austenitic transformation temperature, or martensitic detwinning (a part of the shape memory effect - see Section 1.1.2), when the material is below the austenitic transformation temperature [1, 2].

In this chapter, I present the results of isothermal experiments and modeling of commercially-available Dynalloy Flexinol® SMA springs [8]. The isothermal experiments quantify the force response as a function of the spring end displacement while at a constant temperature. By considering both the virgin and low-cycled states of the material, the analyses aid in the understanding of SMA spring behavior over the course of the lifetime of the device. The organization of this chapter is as follows. First, Section 3.2 details the procedure used in the experiments. Then, Sections 3.3 and 3.4 investigate virgin and low-cycle behavior, respectively. Section 3.3 first presents experimental data on the load-stretch response of virgin springs at various temperatures (Section 3.3.1) and then introduces and applies a numerical model used to quantify the experimental behavior (Section 3.3.2). Section 3.4 has subsections exploring the experimental behavior of low-cycled springs of various spring indices (Section 3.4.1), the experimental response of a single low-cycled spring as various temperatures (Section 3.4.2), the effects of detwinning within the experimental data (Section 3.4.3), numerical modeling of the spring response at various temperatures (Section 3.4.4), and a finite element method procedure for modeling isothermal response curves (Section 3.4.5). Finally, I address the lifetime isothermal behavior of SMA springs in Section 3.5 and conclude in Section 3.6.

3.2 Experimental Procedure

Shape memory alloy (SMA) Flexinol® springs, shape-set from nickel-titanium alloy wire, are purchased from Dynalloy, Inc. [8]. These springs are designed and manufactured in a variety of geometries. All of the spring samples tested are commercially available from Dynalloy and have an advertised transition temperature of 90°C. Geometric parameters and Dynalloy "CS" numbers, an internal identifier code, for the springs tested are provided for each set of experiments.

Isothermal experiments are performed at a variety of temperatures. While the three-dimensional state of stress and strain within the spring is complex and unwieldy [33, 34], the simplified force-stretch relationship for the spring as a whole, determined from these experiments, documents the material response to imperfect transformation. These experiments are performed using the setup described in Section 2.4, in which the spring sample is mounted vertically inside a thermal chamber. Before each test, the offsets between the load cell reading and spring load and between the Instron cross head displacement and the spring displacement are determined using the austenite reference testing procedure described in Section 2.4.1. To perform the isothermal test, the unloaded spring is first heated to 120°C, at which point the material is fully austenite. The spring is then slowly cooled to the desired temperature. The spring expands slightly during cooling due to the two-way effect (see Section 1.1.4). The experiments then utilize displacement control to load and unload the spring.

3.3 Isothermal Experiments and Modeling of Virgin SMA Springs

SMA springs are produced via a heat-treating process that results in a close-packed, helical reference configuration (see Section 1.2). A spring is in its "virgin" state immediately after heat treatment, when it has been neither mechanically loaded or thermally actuated. While springs are generally cycled hundreds, or even thousands, of times in order to ensure stable, repeatable behavior for their use as actuators [36], a thorough documentation of the structural response in the virgin state may aid research efforts investigating material processes that occur during mechanical and thermal cycling.

Figure 3.1: Photograph of a virgin spring sample mounted for isothermal testing.

3.3.1 Experimental Results Varying Temperature

Experiments are performed on spring cut from a length of Dynalloy CS# 4726. The spring has a measured spring index of 5.06 and a wire diameter .43 mm. The spring is mounted vertically inside the thermal chamber as described in Section 2.4. As can be seen in Figure 3.1, the spring is mounted with free-free boundary conditions, meaning that both ends are free to rotate.

A virgin spring sample is used for each curve. The austenitic unloaded reference length is calculated using the same procedure described in Section 2.4.1. The load cell to spring load and Instron cross head position to spring end displacement offsets are first determined using the austenitic reference state testing procedure described in Section 2.4. Then, the cross head is jogged down until load cell is just barely in contact with the drill chuck and the position reading is manually set to zero. The measured length of the collets and Kevlar thread is then subtracted from the cross head position reading at the austenitic reference point constructed from the testing procedure to produce the reference length used in stretch ratio calculations (see Equation 2.4). Isothermal curves are produced using the procedure described in Section 3.2 and a displacement rate of 9 mm per minute. The maximum stretch ratio of 2.5 is selected in order to keep the stretched spring within the bounds of sufficiently-even temperature distribution within the thermal chamber. The resulting isothermal curves are shown at temperatures between 40 and 160°C in Figure 3.2.

The 40 and 80°C results are consistent with those in literature [9, 31]. The 40°C case is a typical martensitic response, transforming from twinned to detwinned martensite over the course of the plateau [25, 26, 76]. The 80°C case shows superelastic response, in which there is little (ideally, no) residual stretch (see Section 1.1.1). The 120 and 160°C cases should also return to their reference states (as in [9, 31]); the fact that they fail to do so indicates that the high loads induced local stress states in excess of the yield stress, causing plastic deformation. This is consistent with the superelastic results in Figure 2.15, in which comparable amounts of plastic deformation were identified at similar load values (despite evidence that the spring loads may have been significantly under-reported - see Section 2.3.3).

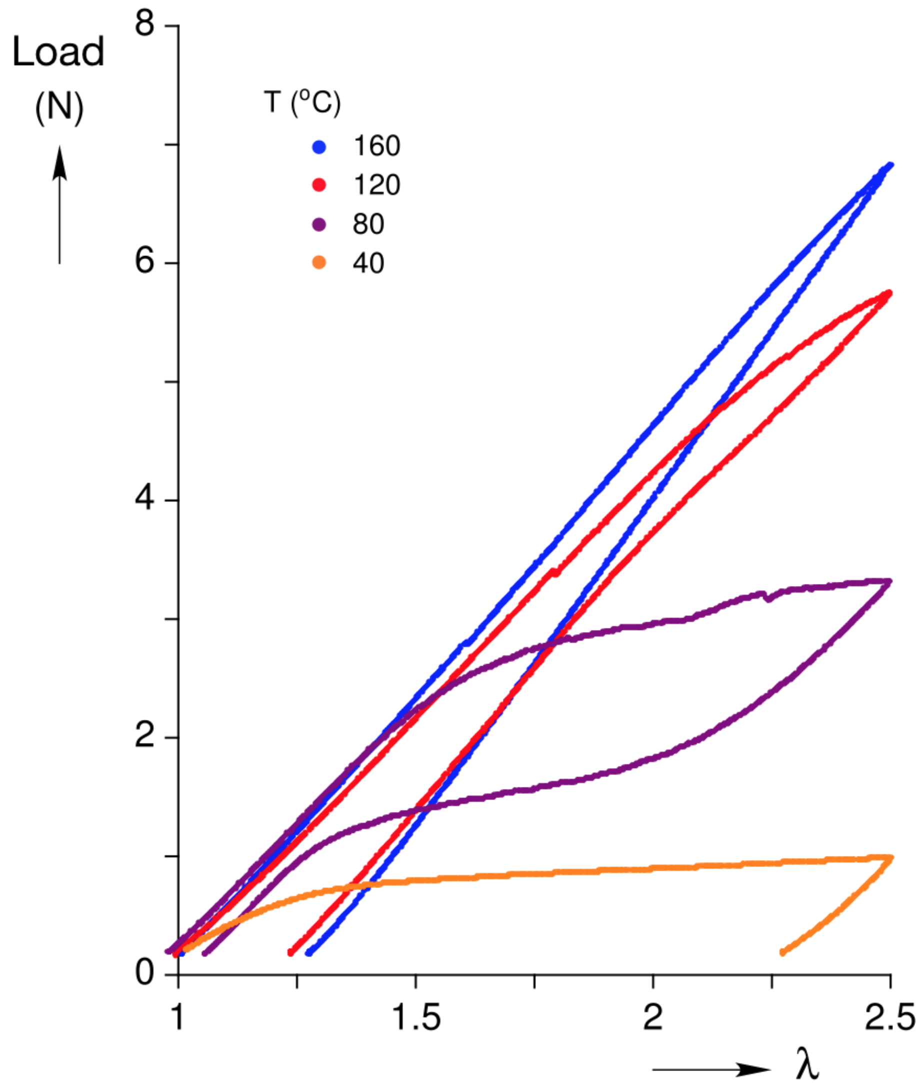


Figure 3.2: Isothermal experimental results on virgin spring samples.

3.3.2 Numerical Modeling of Temperature Variations

A new method is proposed to create a numerical model of the isothermal behavior at various temperatures. Three characteristic points are recorded from each isothermal curve. The first is the amount of two-way effect present upon cooling to the desired temperature (see Section 1.1.4 for a description of the two-way effect). Second, the maximum spring load is noted, which, in our case, always occurs at the maximum stretch ratio of 2.5. The final characteristic point is the residual stretch ratio of the spring upon unloading. This residual stretch is only recoverable by reheating to the austenite state. Because a small amount of tension is maintained in the spring at all times, the amounts of two-way and residual stretch are estimated by the x-intercepts of a linear approximation of the first and last experimental data points, respectively. An example of the determination of the characteristic points is shown in Figure 3.3. These values are plotted against temperature to produce the model shown in Figure 3.4.

The model shows clear trends in the amount of two-way stretch and peak load. The peak load increases with the increasing temperature, as is expected from existing research [1, 31]. The two-way stretch ratio is dictated by the initial slope of curve, corresponding to the spring stiffness, which increases with increasing temperature. (The material is twinned martensite in the 40°C curve and austenite in the other three.) Thus, the two-way stretch ratio is closer to one, which corresponds to the

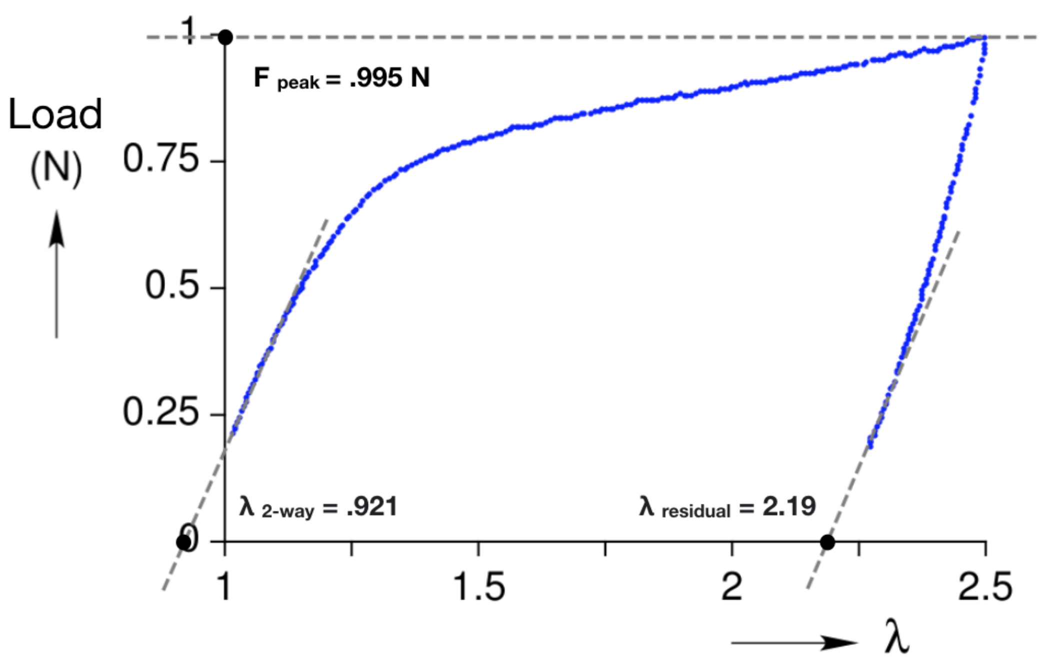


Figure 3.3: Characteristic points for numerical modeling of 40°C isothermal experimental results.

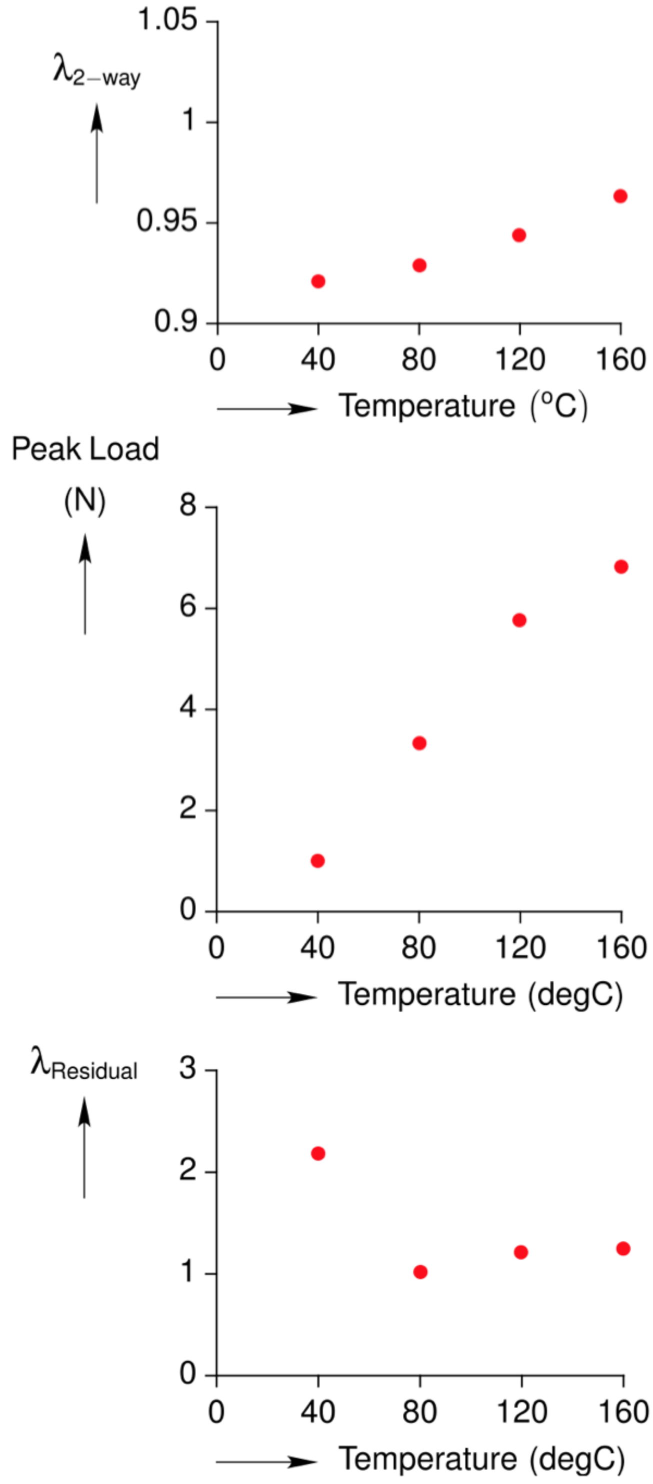


Figure 3.4: Model developed from isothermal experimental results on virgin spring samples.

austenitic reference state, with each incremental temperature increase. However, it is also noted that I would expect the two-way effect to result in stretch ratios greater than one in the martensitic case, based on our observances of Dynalloy SMA spring behavior. This error in our model is caused by the fact that our load and displacement measurements are more precise than our austenitic reference length measurement (which was described in Section 2.4.1). Thus, the austenite reference length was likely over-measured, resulting in decreased stretch ratio values (see Equation 2.4 for the definition of the stretch ratio). Future experiments should both utilize more accurate methods of measuring the austenite reference state as well as maintain a smaller amount of tension in the spring. This will allow for more accurate determination of the stretch state resulting from the two-way effect.

The residual stretch ratio results are almost in agreement with our expectations. As discussed in Section 3.3.1, in the 120 and 160°C tests cases, the spring samples were subjected to stress states in excess of their yield stress, resulting in plastic deformation. Thus, the residual stretch ratios are significantly further from one than I would expect for a superelastic experimental response, as the spring should have returned to its austenite reference state if it were not subjected to plastic deformation [1, 61, 64, 67].

3.4 Isothermal Experiments and Modeling of Low-Cycle SMA Springs

Testing of thermally- and mechanically-cycled (also sometimes called "shaken-down") SMA springs allows for their confident use in applications that require repetitive actuation [36, 77, 78]. The tests in this section are performed on samples that have been cycled on the order of tens of times, showing an intermediate stage in the process of "training" springs for utilization as actuators (see Section 1.1.5) [34, 79].

3.4.1 Experimental Results Varying Spring Index

This set of isothermal experiments is performed at room temperature using Dynalloy Flexinol® SMA springs [8] with a variety of spring indices. The spring sample geometries are detailed in Table 3.1. Note that the spring index parameter is defined in Equation 2.3 in Section 2.2.

Prior to testing, the length of the unloaded sample is measured with a calipers while the sample is heated with a heat gun to keep the material in its austenitic state. This measurement is the reference length in the calculation of the stretch ratio shown in Equation 2.4 in Section 2.3. The ends of the spring sample are threaded onto accurately sized set screws and mounted into collets designed and manufactured by members of Dr. Brei's laboratory in the Mechanical Engineering Department at the University of Michigan. (Since neither of the ends are free to rotate, the spring is said to have "fixed-fixed" boundary conditions.) An example of a mounted sample is shown in the photograph in Figure 3.5. Four spring samples are tested using the procedure described in Section 3.2 and a displacement rate of 5 mm per minute. The experimental results are shown in Figure 3.6.

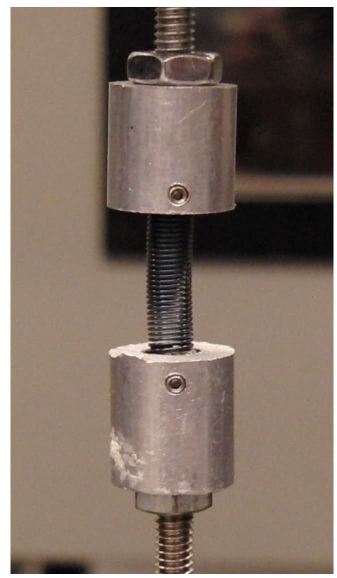


Figure 3.5: Photograph of mounted spring sample with spring index of 8.15.

Table 3.1: SMA spring geometries isothermally tested in experiments on shaken-down springs.

Spring Index	Wire Diameter	Dynalloy CS #	Number of Coils
4.20	.38 mm	4609	36
8.15	.51 mm	unknown	27
11.75	.20 mm	4849	64
20.00	.20 mm	4613	76

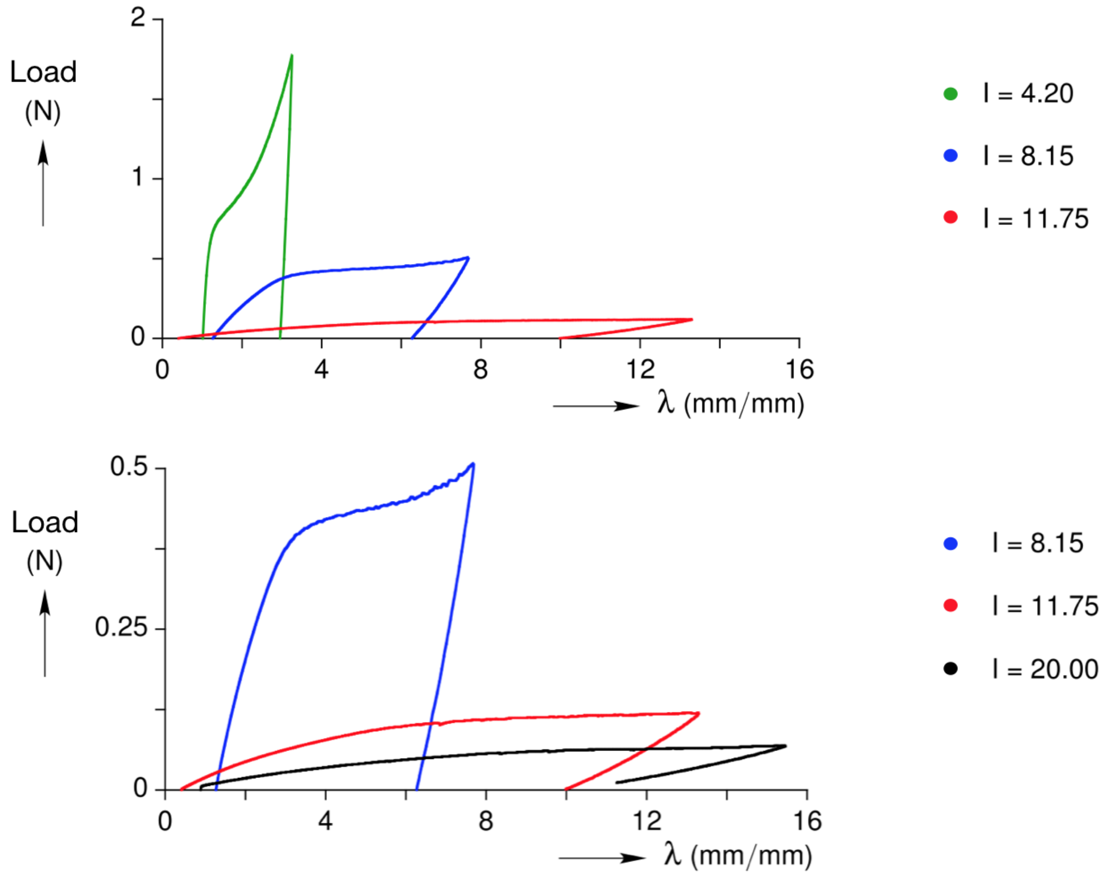


Figure 3.6: Isothermal experimental results on shaken-down spring samples of various spring indices.

In the martensitic curves presented in Figure 3.6, we can observe the predictable trend of the martensitic plateau, maximum load, and spring stiffness all decreasing with increasing spring index; in contrast, the maximum stretch ratio and, thus, displacement of the spring increases with increasing spring index. This is logical because the spring index, defined to be the ratio of the coil diameter to the wire diameter, is higher for springs that are "flimsy" and lower for springs that are "stiff". While SMA springs carry varying amounts of axial, bending, and torsional stresses as they stretch [33, 34], the stiffer, low-spring-index springs carry greater stresses in the axial direction as opposed to torsionally, and the flimsier, high-spring-index springs carry greater torsional stresses rather than axial ones. These results are consistent with those reported in the literature [26, 42].

One effect of increased torsional stresses in springs with high spring indices is the observable torsional buckling that occurs as the spring is allowed to cool before loading begins. Note from Section 3.2 that the Instron cross head is first positioned such that there is zero load on the austenitic spring. Predictably, for low-spring-index springs, cooling causes the load cell to read a negative load due to the two-way effect described in Section 1.1.4; as the spring attempts to elongate, it applies a compressive force to the load cell. However, for sufficiently high-spring-index springs, this compressive force is not read by the load cell. This is not due to a lack of two-way effect; the elongation of the spring upon cooling is still observable with at least one free end condition. Rather, the fixed end conditions of the spring and the increased torsional stress carried due to its geometry cause it to exhibit a torsional buckling instability. Essentially, the spring doesn't only want to "spread out", but it also wants to "untwist" or "unscrew". A photograph of this phenomenon is shown in Figure 3.7.

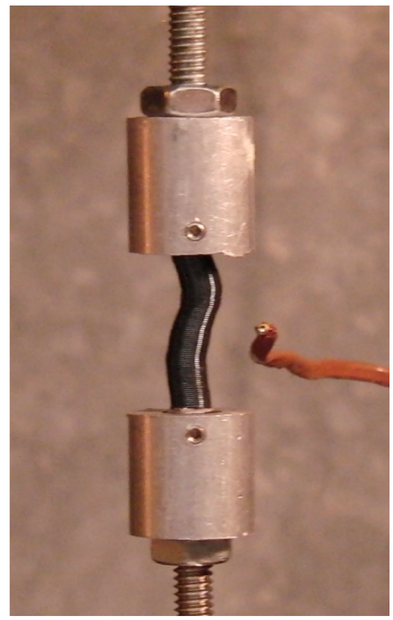


Figure 3.7: Photograph of torsional buckling instability occurring in a mounted spring sample with spring index of 20.00.

3.4.2 Experimental Results Varying Temperature

This set of isothermal experiments is performed at various temperatures using a single sample of a commercially-available Dynalloy Flexinol® SMA spring [8]. The spring sample tested is a Dynalloy CS# 4608 with a measured spring index of 5.00 (see Equation 2.3), a wire diameter of .43 mm, and an advertised austenitic transition temperature of 90°C. The sample has 34 coils.

The spring sample is mounted vertically inside the thermal chamber as described in Section 2.4. The boundary conditions are fixed-free, as the bottom end of the spring is clamped and the top end is free to rotate (see Figure 3.8). The load cell to spring load and Instron cross head position to spring end displacement offsets are determined using the austenitic reference state testing procedure described in Section 2.4.1 prior to testing. The reference length of the sample is determined by first manually setting the position reading to zero when the cross head is jogged down until load cell is just barely in contact with the drill chuck. Then, the measured length of the collet and Kevlar thread is subtracted from the cross head position reading at the austenitic reference point constructed in the reference point testing procedure. Isothermal curves are produced using the procedure described in Section 3.2 and a strain rate of one per minute. The maximum stretch ratio of $\lambda = 4$ is determined from the plastic deformation testing results described in Section 2.3.3 and shown in Figure 2.16. The results of isothermal testing on a single low-cycle spring sample at various temperatures are shown in Figure 3.9.

Figure 3.8: Photograph of mounted low-shakedown spring sample for isothermal testing of temperature variations.

Experiments in literature have shown that spring loads increase with increasing temperature during isothermal testing [9, 31], as was discussed in Section 3.3.1. This behavior is clearly observed between 53 and 70°C in Figure 3.9. However, between 31 and 43°C, the spring loads appear to be decreasing with increasing temperature, and they do not vary significantly between 43 and 53°C. This phenomenon has not

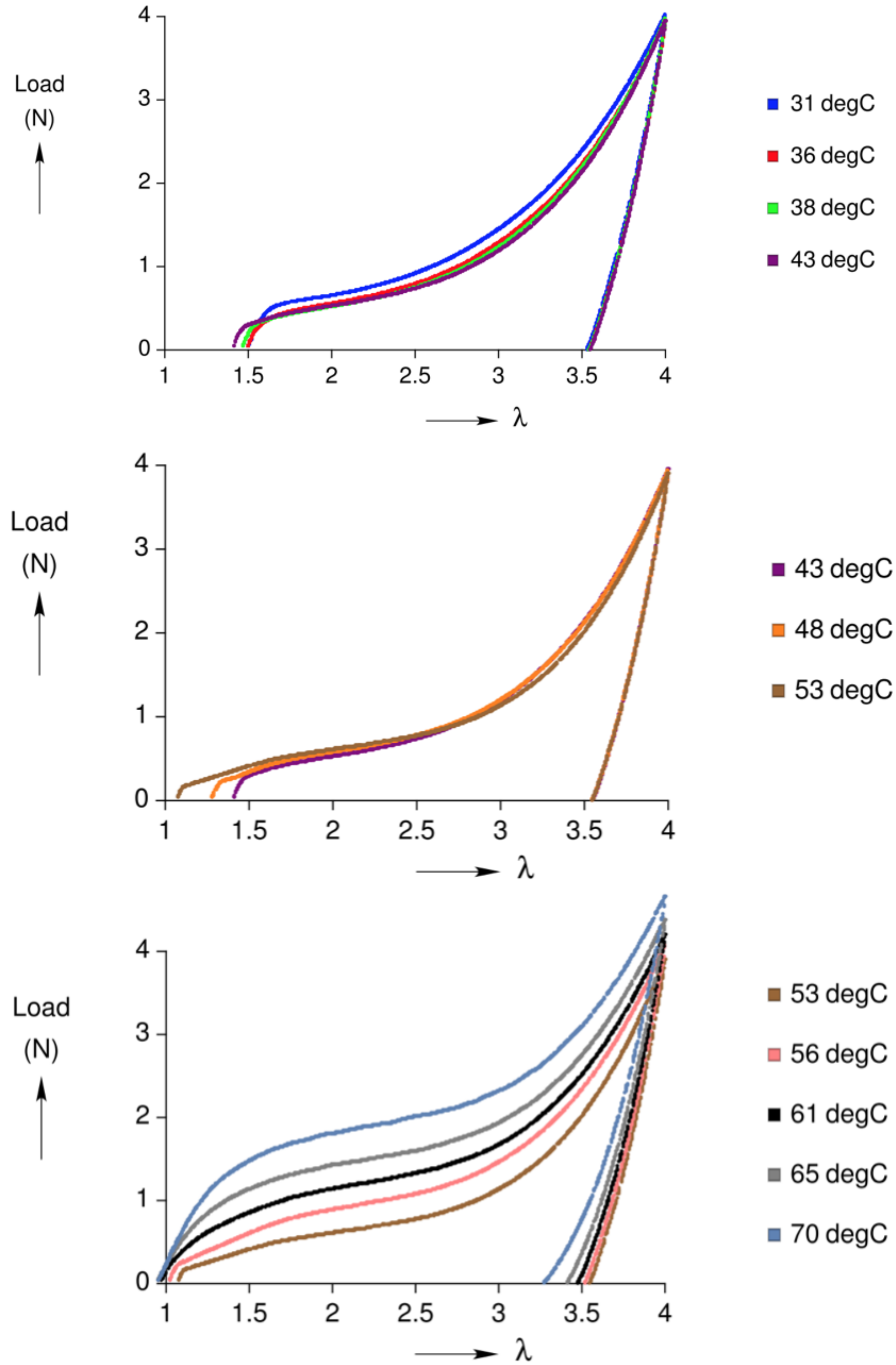


Figure 3.9: Isothermal experimental results on low-cycle springs at various temperatures.

previously been identified in the literature.

Recall that, before every isothermal experiment, the spring was heated to austenite and then cooled to the desired temperature. Also, materials scientists have identified that there exist 24 variants within the martensitic phase structure, and thus, many different possible combinations of these variants [3]. It is suspected, then, that the 31 to 43°C curves may be demonstrating the transformation from one self-accommodated martensitic combination of variants to detwinned martensite, while the 53 to 70°C curves transform from another combination of variants to detwinned martensite. The 43 to 53°C curves then exhibit the boundary between these two distinct combinations of martensitic variants. The second combination of variants of twinned martensite could instead be R-phase, as this intermediate phase state exists in some SMA materials between the austenite and twinned martensite phases [2, 37].

It should also be noted that, because the spring response changes slightly with cycling, the fact that the tests were not performed in regular order in regards to temperature could have a small effect on individual curves. However, this effect is not expected to be significant in terms of the trends shown in the model.

3.4.3 Effects of Martensitic Detwinning

Due to the high level of precision in the experimental data, we can zoom in on the onset of martensitic detwinning within the isothermal curves and observe a repeated abnormality in the data (see Figure 3.10). The consistent sudden decrease in force at the beginning of the martensitic plateau is assumed to correspond to the immediate local stress relaxation that occurs as the material begins to transform to detwinned martensite. This is the first known instance of visible martensitic detwinning phase transformation in isothermal experimental data.

The load at the onset of martensitic detwinning is plotted against temperature in Figure 3.11. The results show that the transformation load increases with increasing

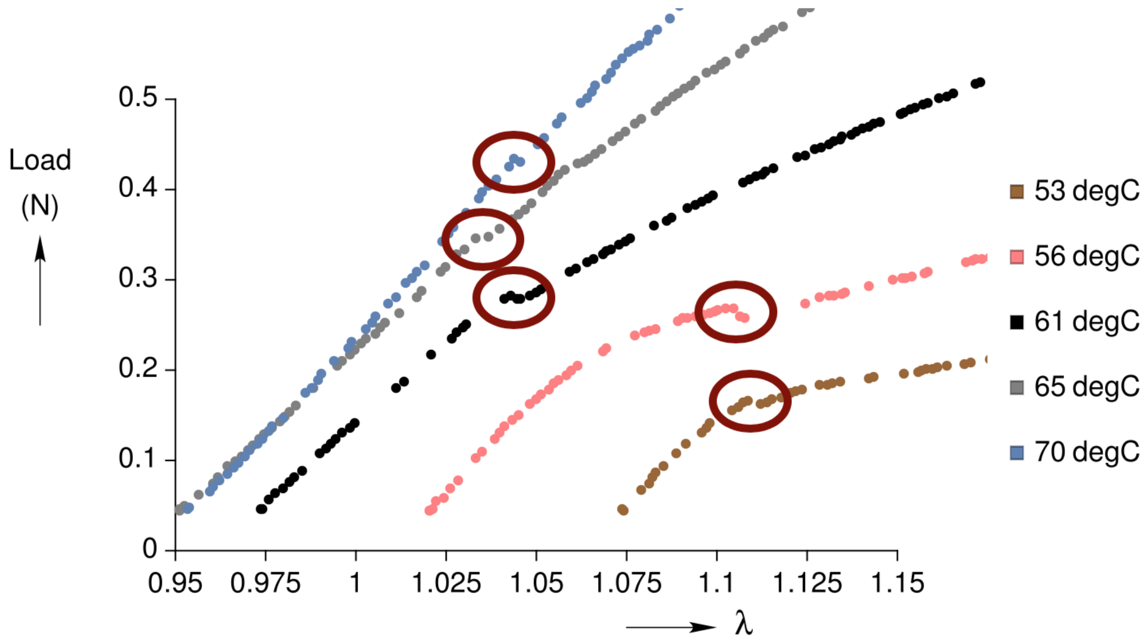


Figure 3.10: Martensitic detwinning within isothermal experimental results on low-cycled spring samples.

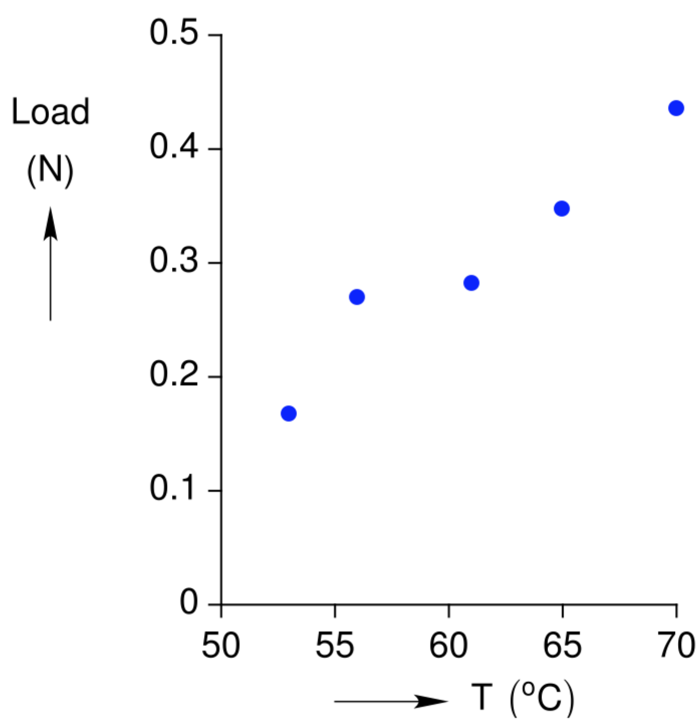


Figure 3.11: Load at onset of martensitic detwinning as a function of spring temperature during isothermal testing.

temperature within the range of temperatures at which the transformation is visible. The transformation is not visible at temperatures below 53°C. No experiments were conducted at temperatures over 70°C.

Referring back to the rotational phenomenon that was seen during isothermal testing of low-cycled samples in the horizontal configuration (see Section 2.3.4), it is presumed that changes in the local stress state due to the martensitic detwinning process may result in the observed change in the direction of the spring end rotation at some critical point. Further experiments tracking the spring end rotation should be performed in order to test this hypothesis.

3.4.4 Numerical Modeling of Temperature Variations

The same numerical modeling procedure is performed as was described in Section 3.3.2. The amount of two-way stretch present upon cooling, the maximum spring load (at a stretch ratio of 4), and the residual stretch ratio of the spring upon unloading are plotted against the temperature for each isothermal curve. The temperature-dependent model for this low-cycled spring sample is shown in Figure 3.12.

The model clearly shows that a temperature in the vicinity of 50°C is somehow critical. While the two-way stretch decreases to one with increasing temperature as expected (see Section 1.1.4), there is an inflection point at around 50°C. The peak load decreases to a minimum at around 50°C before increasing as expected, which corresponds to the overall load pattern discussed in Section 3.4.2. There also appears to be a local maximum in the residual stretch at around the same temperature. It seems logical that the residual stretch would decrease with increasing temperature, since the material is approaching the temperature at which it would not transform at all from its austenitic state; in that case, the material should be superelastic and would have no residual stretch [2, 9, 26, 31, 42, 61, 62, 64, 67]. Thus, the model clearly shows a difference in behavior between cooling to a temperature below the

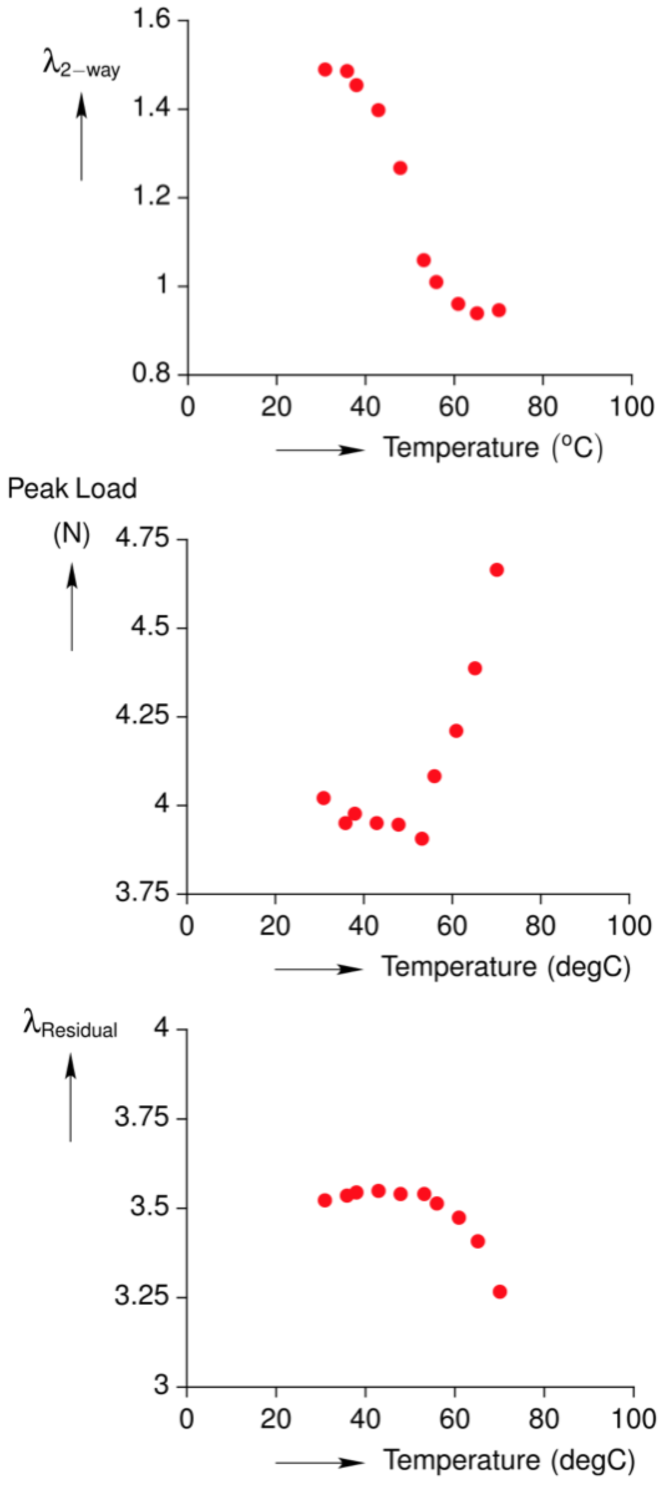


Figure 3.12: Model developed from isothermal experimental results on shaken-down spring samples.

critical temperature and to a temperature above it. I suspect that this may illustrate isothermal response from the two distinct combinations of martensitic variants (or one combination and R-phase) from which the spring transforms during the test (see Section 3.4.2).

3.4.5 Finite Element Analyses

The results in Section 3.4 help illustrate why it would be advantageous to be able to identify local stresses within the spring. The stress and strain states within an SMA spring during either thermally- or mechanically-induced actuation are affected by the complex and changing relationship between axial, bending, and torsional stress caused by the spring's geometry [33, 34]. Finite element analyses have previously been performed on SMA springs such as in the works by Toi et al. and Lee et al. [62, 64], who employed a one-dimensional Brinson model, and Mirzaeifar et al. [80], who used the three-dimensional constitutive relationship developed by Qidwai and Lagoudas [81]. I have not, however, been able to locate literature employing finite element analyses in isothermal cases that are not superelastic. Here, I therefore present another method of finite element simulation of SMA spring structures: modeling the martensitic isothermal experimental behavior as a result of plastic deformation.

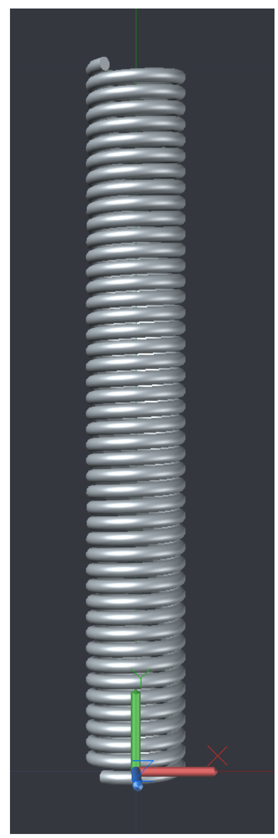


Figure 3.13: Spring modeled in AutoCAD 3D.

A three-dimensional helix with the properties of our low-cycled experimental sample (CS# 4608, measured spring index of 5.00, a wire diameter of .43 mm, and 34 coils) was constructed in AutoCAD 3D (see Figure 3.13) and then imported into Abaqus as a solid deformable body. The nodes in the end coils are tied to rigid, non-deformable shell structures constructed in Abaqus to model the effect of fixed-fixed boundary conditions. A mesh is applied composed of quadratic brick elements with aspects ratios of approximately 1x1x2, with the elongated dimension along the length of the wire. There are approximately 6 elements across the diameter of the wire and 80 along the length of a single coil of the spring. The mesh and boundary conditions are shown in Figure 3.14.

While Abaqus does have a built-in material model intended to model nickel-titanium shape memory alloy material, this constitutive relationship models superelasticity - not the shape memory effect [82]. Thus, the model assumes that the mechanical response is not dependent on temperature; it instead states that austenitic transition occurs at specified values of stress. Alternatively, Abaqus's built-in J2 elasto-plastic constitutive model with linear isotropic hardening is used to capture martensitic detwinning behavior [83]. This linear isotropic model defines the constitutive behavior from a pair of points input in the form $(0, \sigma_o)$, (ϵ_p, σ), where σ_o is the initial yield stress, ϵ_p is a finite plastic strain value, and σ is the stress at that

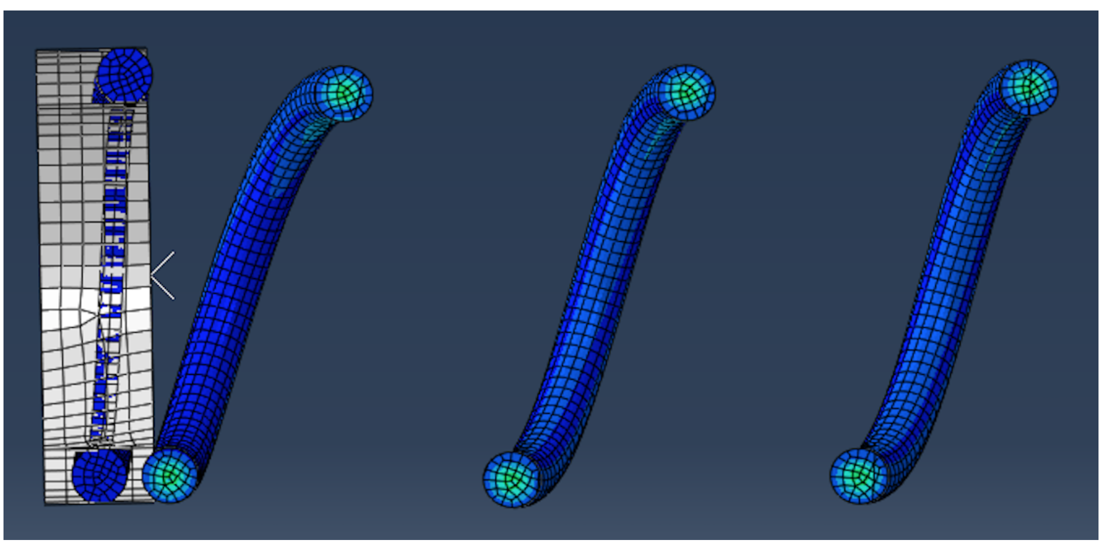


Figure 3.14: Finite element modeling of SMA spring showing meshing and boundary conditions.

value of plastic strain. The linear isotropic hardening modulus C is then given by

$$C = \frac{\sigma - \sigma_o}{\epsilon_p} \tag{3.1}$$

More data points are input into Abaqus to model C changing in a piecewise fashion. Because dramatic changes in C cause Abaqus to fail in executing the model, multiple piecewise segments are added to the constitutive model when this occurs, providing several incremental steps to change the value of the isotropic hardening modulus.

The case that is modeled is the 31°C experimental result on a low-cycled spring, which is taken from the first plot in Figure 3.9. The axial displacement of one end collet is prescribed while the other end collet is held in place. The resulting load vales at the pulled end of the spring are returned by Abaqus. The piecewise yield stresses and plastic strain values in the constitutive model are calibrated with the experimental results to match those predicted by the model, as shown in Figure 3.15. The resulting constitutive model is shown in Figure 3.16.

This model demonstrates the ability to investigate the local three-dimensional states of stress and strain within the spring during loading and unloading. Future work should utilize this model construction to better quantify the trade-off that occurs between axial, bending, and torsional stresses during actuation, which may be useful in investigating the material-related phenomena presented in this thesis.

3.5 Lifetime Isothermal Behavior of SMA Springs

A comparison of the differences between the virgin and low-cycle spring experiments is shown in Table 3.2. The isothermal numerical models for virgin (see Section 3.3.2) and low-cycled springs (see Section 3.4.4) are presented together in Figure 3.17. This allows us to compare the 40 and 80°C martensitic behavior of the virgin samples against behavior in that temperature range of a spring that has been cycled.

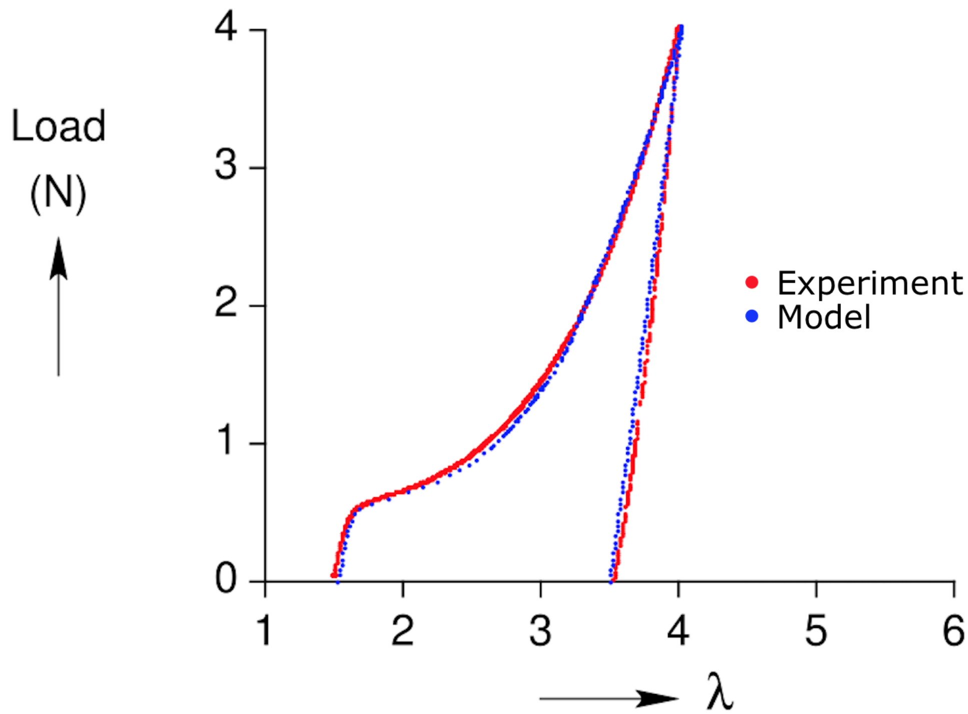


Figure 3.15: Isothermal experimental and finite element model results.

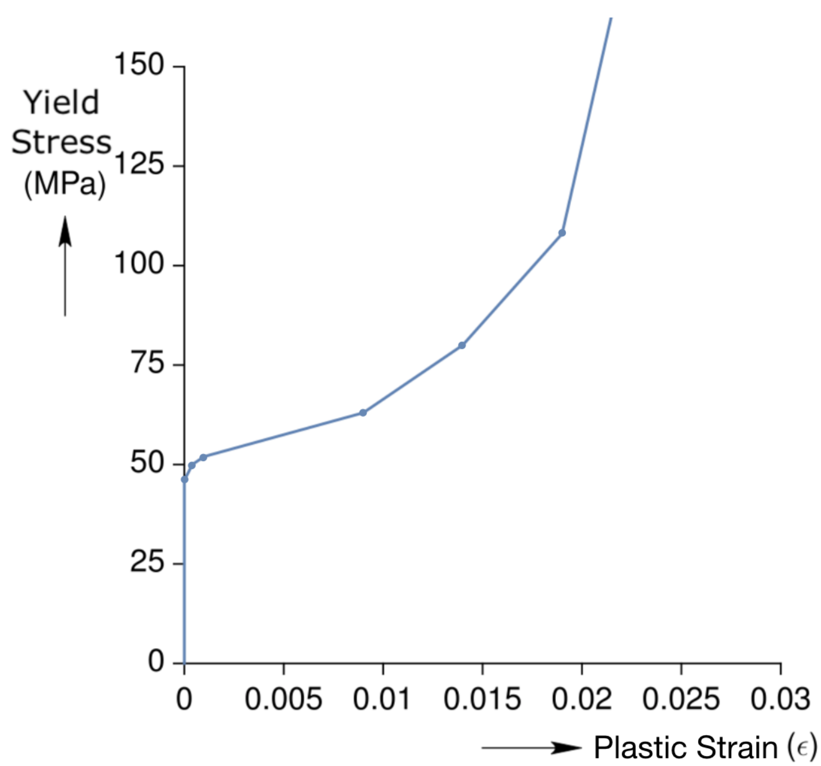


Figure 3.16: J2 plasticity constitutive model.

Table 3.2: Experimental differences in isothermal SMA spring results included in Figure 3.17.

Cycling	Coil Dia.	B.C.s	Temp. Range	Results
First	2.18 mm	Free-free	40 - 160°C	Fig. 3.4
Tens	2.15 mm	Fixed-free	40 - 80°C	Fig. 3.12

Looking at the slopes of the lines between 40 and 80°C for virgin springs, they appear to be relatively similar to those of the highest-temperature data points for the low-cycled spring sample. This might suggest that the virgin springs cooled only to the second combination of variants of martensite (or perhaps R-phase) discussed in Section 3.4.4 and that the lower-temperature combination of martensitic variants only appears upon cycling. The peak load and residual stretch are also significantly higher for the low-cycle spring. While thermomechanical cycling has typically been shown to decrease spring stiffness [28, 33–35], some experiments have seen instances of stiffening [19, 63], and no experimental data could be located on martensitic mechanical cycling at a constant temperature. Additionally, the increase in residual stretch upon cycling despite the higher peak load implies that the unloading stiffness increases with cycling. Alternatively, the virgin springs may be of a different material composition than the low-cycled springs or have experienced different heat treating methods (see, for example, [20]). Experiments should be performed on spring samples known to have identical material compositions and histories, both at a wider variety of temperatures and with different amounts of cycling, in order to better document and explain the trends shown in this numerical model.

3.6 Conclusion

This chapter has presented experimental results from isothermal tests on virgin and low-cycle springs along with techniques for numerical characterization and finite element modeling. The primary contribution of this work is the finding of two dis-

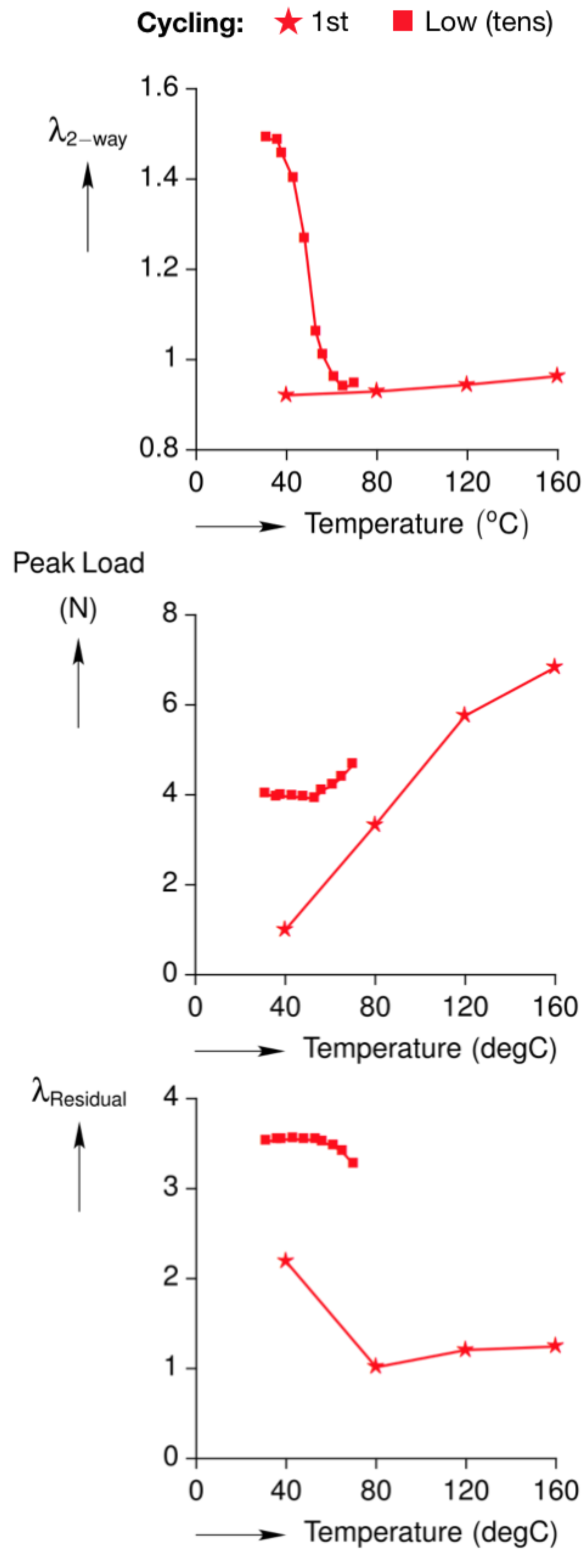


Figure 3.17: Numerical model of lifetime isothermal cycling results.

tinct behaviors within the commonly understood twinned-to-detwinned martensitic response dependent on temperature. The proposed numerical modeling scheme identifies a critical temperature of approximately 50°C separating the distinct responses. The high-precision experimental data also visibly shows the onset of detwinning in isothermal testing. Examples of this could not be located in existing literature, suggesting another contribution of this work. Finite element modeling using J2 plasticity is shown to produce a load versus stretch response in excellent agreement with experimental results, which may enable improvements on our current level of understanding of stress and strain behavior during mechanical actuation of SMA springs. Future work could build on these findings in order to advance both material and structural knowledge of martensitic phase transformations and cycling.

CHAPTER IV

Thermomechanical Experiments and Modeling of SMA Springs

4.1 Introduction

This chapter is concerned with the thermomechanical response of shape memory alloy (SMA) tension springs at constant load values; these tests are also called "dead load" tests. Scientifically, these tests provide a better understanding of SMA spring response during phase transformation. Practically, these experiments are useful in modeling SMA spring behavior for applications as actuators (see Section 1.2.1) [77, 78]. Thermomechanical testing of SMA tension springs has been demonstrated in a number of publications in various states of material composition, spring geometry, and thermal cycling [19, 20, 22, 26, 28, 33–35, 38, 39, 58–60, 63, 66, 84, 85]. The experiments and modeling within this chapter consider the effects of geometry and cycling on the displacement-temperature response of one type of commercially-available SMA springs.

This chapter documents the responses of virgin and low-cycled Dynalloy Flexinol® SMA springs [8]. In conjunction with Churchill's documentation of the response of a similar high-cycled Dynalloy spring [58], this analysis is helpful in understanding the lifetime actuation behavior of Dynalloy springs. The chapter is laid out as follows. Section 4.2 describes the thermomechanical testing procedure. Sections 4.3 and 4.4 contain experimental and modeling results on virgin and low-shakedown SMA springs, respectively. Section 4.3 begins with analyses on variations in load, including subsections on the experimental results (Section 4.3.1), the effects of the boundary conditions on the experimental results (Section 4.3.2), the presence and impact of R-phase in the experimental results (Section 4.3.3), and the description of a method of numerical modeling that is applied to the experimental data (Section 4.3.4). The section ends with a final subsection on the effects of thermal cycling (Section 4.3.5). A similar selection of topics are covered in Section 4.4 pertaining to low-shakedown springs. First, experimental results on load variations are again presented (Section 4.4.1), followed by the application of the numerical procedure (Section 4.4.2). Then, the effects of thermal cycling are shown, both in terms of experiments (Section 4.4.3) and numerical modeling (Section 4.4.4). In Section 4.5, the virgin and low-shakedown thermomechanical actuation behavior are discussed and compared to Churchill's high-shakedown behavior [58]. Conclusions are drawn about the behavior of Dynalloy SMA springs over the course of their lifetime. The chapter closes with a summary of its contributions and their implications in Section 4.6.

4.2 Experimental Procedure

Testing is performed using the vertical experimental configuration and setup described in Section 2.4. The austenitic unloaded reference length is calculated using the same procedure described in Section 3.4.2. The load cell to spring load and Instron cross head position to spring end displacement offsets are first determined using the austenitic reference state testing procedure described in Section 2.4.1. The cross head is jogged down until the LRF400 axial load cell [70] is just barely in contact with the drill chuck and the position reading is manually set to zero. The measured length of the collet and Kevlar thread is then subtracted from the cross head position reading at the austenitic reference point constructed from the testing procedure to produce the reference length used in stretch ratio calculations (see Equation 2.4 for the definition of the stretch ratio). To generate a dead load curve, the thermal chamber is first heated to 120°C before data collection begins. The desired constant load is applied and maintained by Partner's internal PID load control program, to which the load cell has been calibrated. Liquid nitrogen is used to cool the thermal chamber, which is then heated back to 120°C. Load control at the desired values is maintained throughout the thermal cycle.

All springs tested are commercially available Flexinol® nickel-titanium SMA tension springs purchased from Dynalloy, Inc. [8]. These springs have an advertised austenitic transformation temperature of 90°C. The geometric parameters and Dynalloy "CS" numbers, an internal identifier code, of springs tested are provided for each set of experiments described.

4.3 Thermomechanical Experiments and Modeling of Virgin SMA Springs

I refer to "virgin" SMA springs as those that have been freshly shape-set via heat-treating (see Section 1.2) and have not yet undergone any additional thermal actuation. Existing research has tended to focus on highly cycled, or "shaken-down", spring specimens, due to the stable, predictable behavior that allows for their confident application as actuators [36]. However, accurate experimental results documenting the spring response prior to the shakedown process may aid research in the material-level processes that are occurring during thermal cycling.

4.3.1 Experimental Results of Load Variations

The samples tested are cut from a length of Dynalloy CS# 4726, which has an advertised transition temperature of 90°C. The spring has a measured spring index of 5.06 and a wire diameter .43 mm. The ends of each sample are threaded onto standard No. 2 set screws and secured in place with a thin layer of high-temperature adhesive. Kevlar thread is attached to both set screws; thus, this set of experiments is performed using free-free boundary conditions. Figure 4.1 shows a photograph of a sample during testing. Three Omega thermocouples are installed: one measures the temperature of the bottom end of the spring and two monitor the ambient temperature at either end [75]. The thermocouple that is attached to the bottom set screw has very little stiffness so as not to interfere with the mechanical results. The experimental procedure is described in Section 4.2, above. Experimental results on virgin spring samples are shown in Figure 4.2.

Figure 4.1: Photograph of a virgin spring sample mounted for thermomechanical testing.

The virgin samples exhibit an interesting turnaround behavior: the maximum stretch ratio increases with increasing load from .25 N to 1 N, then decreases with increasing load from 1 N to 1.75 N. The turnaround occurs again as the maximum stretch ratio increases with increasing load from 1.75 N to 2 N. Non-monotonic thermomechanical experimental results such as these have been seen in the literature previously in the work of Gonzalez and Oliveira [19, 20, 63]. Their experiments are performed on virgin samples shape-set in-house. The authors suggest that this turn-

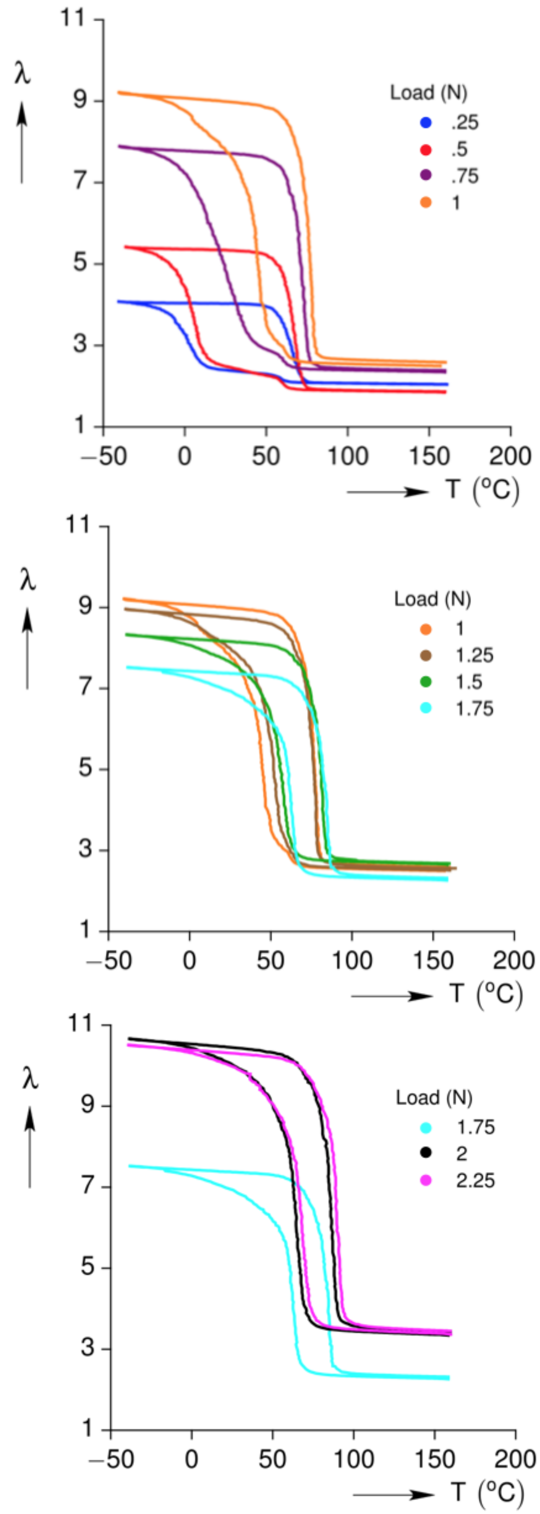


Figure 4.2: Thermomechanical experimental results on virgin spring samples.

around behavior maybe be due to the suppression of R-phase transformation above a certain range of load values. (I discuss this further in Section 4.3.3.) Oliveira et al.'s results also suggest that the amount of time spent heat-treating may have an effect on the presence and magnitude of this turn-around behavior [20]. I am not privy to the heat-treating methods used by the manufacturer, so I am unable to compare them with Oliveira et al.'s results.

It should also be noted that there is an observable difference in behavior between two different samples, despite the fact that all the samples were taken from the sample length of spring purchased from Dynalloy. These results are shown in Figure 4.3. This result demonstrates that significant discrepancies in the thermomechanical results, such as the apparent turn-around behavior between 2 and 2.25 N in Figure

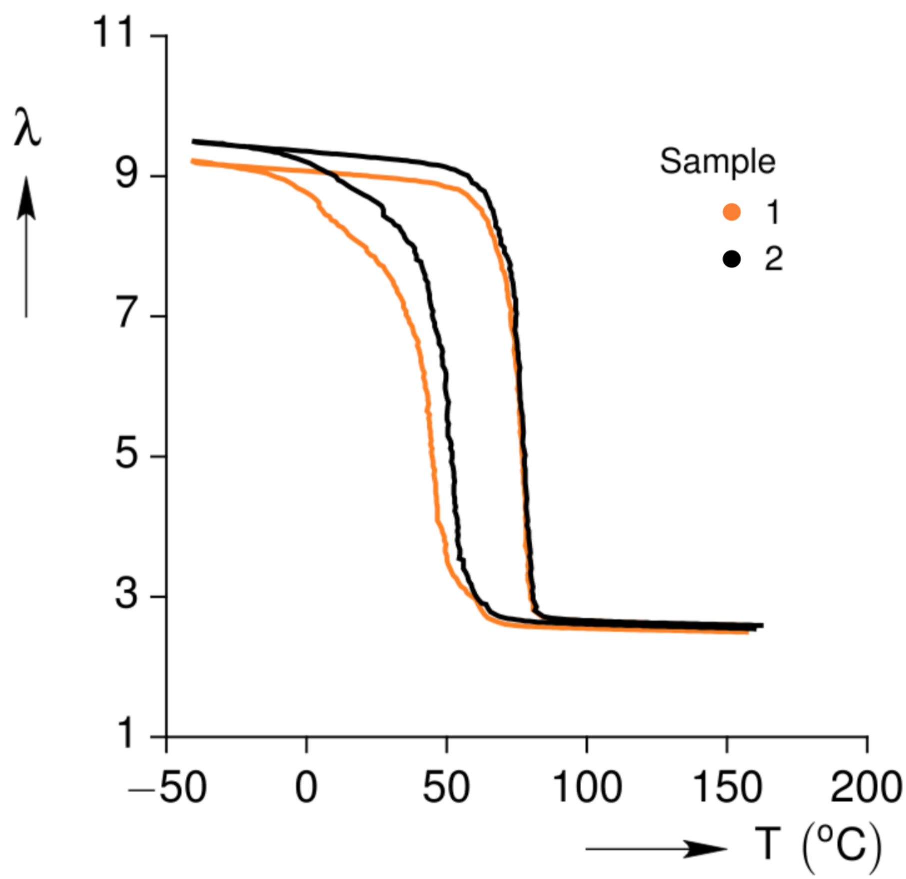


Figure 4.3: Thermomechanical testing of two virgin samples at a load of 1 N.

4.2, are within the error that exists along the length of a single manufactured spring. The thermomechanical response at load values above 2.25 N would need to be tested in order to determine if there is in fact a second drop occurring in the vicinity of a load value of 2 N.

4.3.2 Effects of Boundary Conditions

Two possible sets of boundary conditions are tested using a sample that has been actuated before, but only a few times; thus, this sample's behavior is much closer to that of a virgin sample than that of a shaken-down spring. The sample tested is a Dynalloy CS# 4726 with a measured spring index of 5.00 and wire diameter of .43 mm. Thermomechanical testing results at a load of .1 N using fixed-free and free-free boundary conditions are shown in Figure 4.4. (Note that the terms "fixed" and "free" are in regards to the ability of the end of the spring to rotate, or the lack thereof).

Dhakal et al. [34] and Saleeb et al. [33] analyzed the impact of fixed-fixed and fixed-free boundary conditions in similar thermomechanical tests. They found that, while the difference in the axial displacement of the spring was not significant, the fixed-free spring was able to achieve slightly larger stretch ratios due to its ability to "unwind". They showed this result both experimentally [34] and using finite element modeling [33]. It seems likely, then, that free-free boundary conditions would result in further increases in stretch, as both ends are able to unwind in order to relieve torsional stresses as they develop.

4.3.3 Effects of R-Phase Transitions

At low load values, SMA material transforms first to R-phase and then to martensite upon cooling from austenite; at high loads, the R-phase is suppressed and the material transforms straight to martensite [2, 37, 38]. R-phrase phase transformation

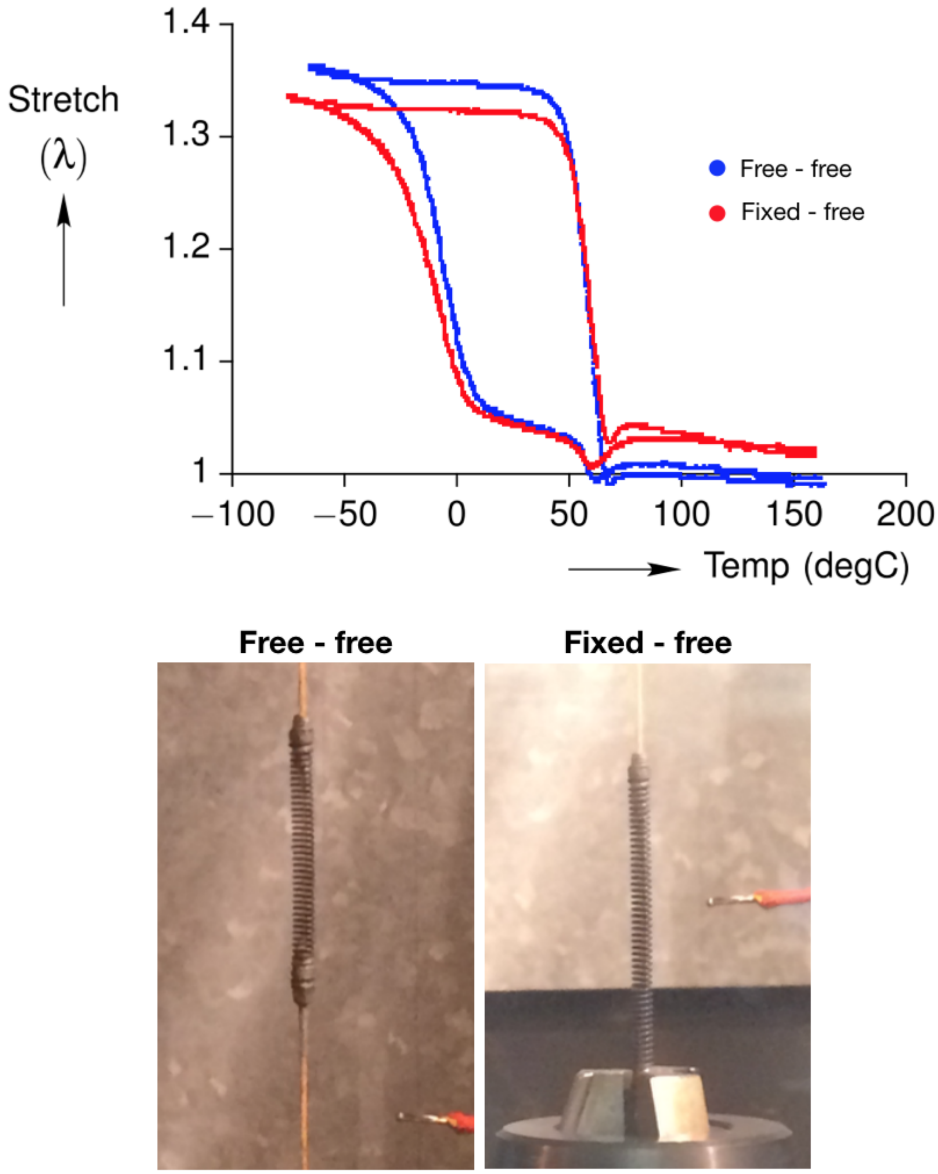


Figure 4.4: Boundary conditions used for thermomechanical testing and results at a constant load of .1 N.

is visible at low load values in Figure 4.2, up to and including 1 N. Above a 1 N load, the R-phase transformation is no longer visible. R-phase is also visible during thermomechanical experiments reported in the literature [20, 26, 38, 39, 59, 66]; Gedouin et al. successfully modeled this effect of R-phase in the thermomechanical response of SMA springs as well as its suppression at high load values [66].

R-phase transformation during thermomechanical testing corresponds to a reversal in the direction of torsional rotation of the spring as was observed during isothermal testing of shaken-down springs (described in Section 2.3.4). In the .1 N load case, unlike in higher load cases, R-phase transformation and change in rotational direction corresponds to a change in stretch direction as well; this can be seen in Figure 4.4. Figure 4.5 looks more closely at the occurrence of R-phase transformation in the free-free boundary condition case. Note that, at load values above .1 N and below 1 N, the R-phase transformation no longer produces a change in stretch direction, but the torsional direction reversal still occurs. This phenomenon occurred with various collet types, as long as the end was free to rotate, and has not been identified in existing literature.

At loads between 1 and 1.75 N, R-phase is no longer visible in the experimental data. Thus, it is clear from our results that the turn-around behavior - the decrease

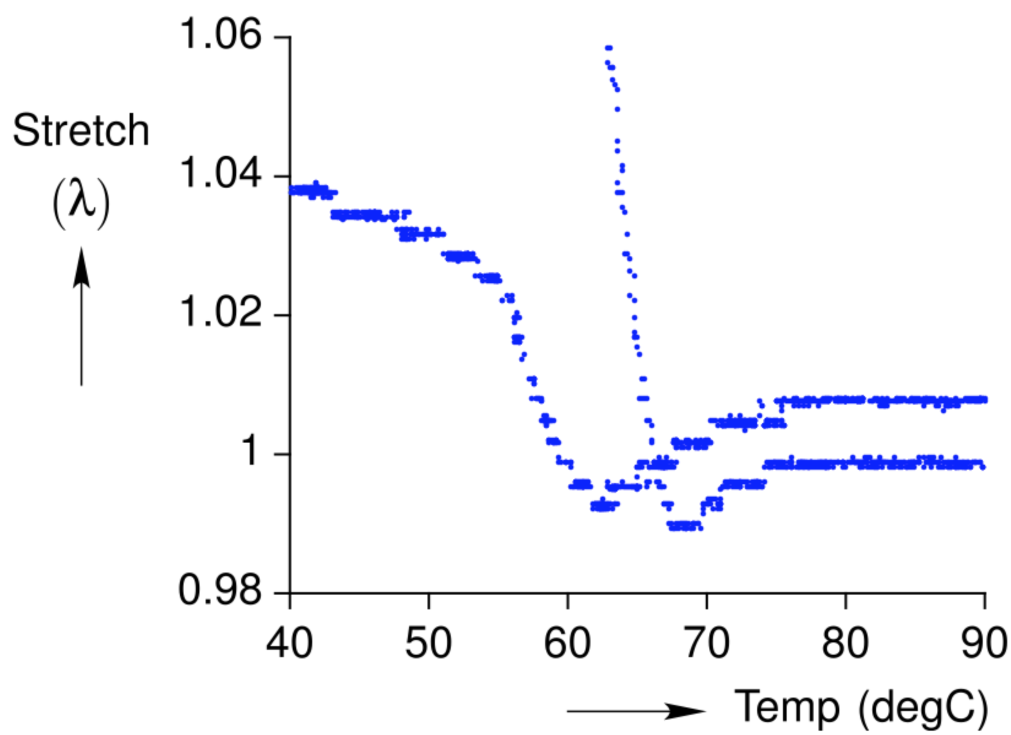


Figure 4.5: R-phase transformation during thermomechanical testing with free-free boundary conditions and a load of .1 N.

in stretch that occurs between 1 and 1.75 N - takes place at the first load values in which R-phase transformation is actively suppressed, suggesting that this may be a structural response to a material phenomenon. At loads above 1.75 N, the response may be monotonic; further experiments should be performed to verify this.

4.3.4 Numerical Modeling of Load Variations

The numerical model employed in Churchill's 2011 thermomechanical analysis of SMA springs [58] is applied to the thermomechanical experimental results shown in Figure 4.2. This model predicts the thermomechanical stretch-temperature behavior at constant load values. In developing this model, it is noted that the experimental curve is of a similar shape to that of the equation of stability of a rigid bar attached to the ground by a torsional spring (of rotational stiffness k_θ) with an initial rotational imperfection θ_o undergoing rotational displacement θ caused by a vertically-applied point force P at the tip of the bar. A schematic representation of this problem is shown in Figure 4.6. The equilibrium equation is thus

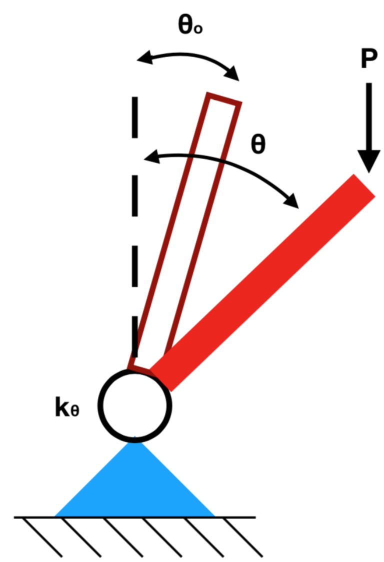


Figure 4.6: Schematic representation of stability problem corresponding to numerical model.

$$P(\theta) = \frac{k_\theta(\theta - \theta_o)}{L\ sin\theta} \tag{4.1}$$

$P(\theta)$ can be re-written as $T(\lambda)$ in terms of five parameters:

$$T(\lambda) = T_o - T_1 \left(\frac{\lambda - \lambda_A - \lambda_I}{\lambda_M - \lambda_A} \right) \csc \left(\frac{\pi(\lambda - \lambda_A)}{\lambda_M - \lambda_A} \right) \tag{4.2}$$

where λ_A and λ_M are the austenitic and martensitic stretch ratio asymptotes, respectively, λ_I governs the curvature of the curve, T_o is a reference temperature, and T_1 is related to the maximum slope of $\lambda(T)$. Equations 4.1 and 4.2 are related by the following equations:

$$\begin{aligned} P(\theta) &= T(\lambda) - T_0 \\ \pi\frac{k_\theta}{L} &= T_1 \\ \theta &= \pi\frac{\lambda - \lambda_A}{\lambda_M - \lambda_A} \\ \theta_o &= \pi\frac{\lambda_I}{\lambda_M - \lambda_A} \end{aligned} \tag{4.3}$$

Equation 4.2 is applied as the fitting function for each of the load values between .25 N and 2.25 N shown in Figure 4.2. Curves are fit for both heating and cooling. An example of the numerical fits is shown in Figure 4.7.

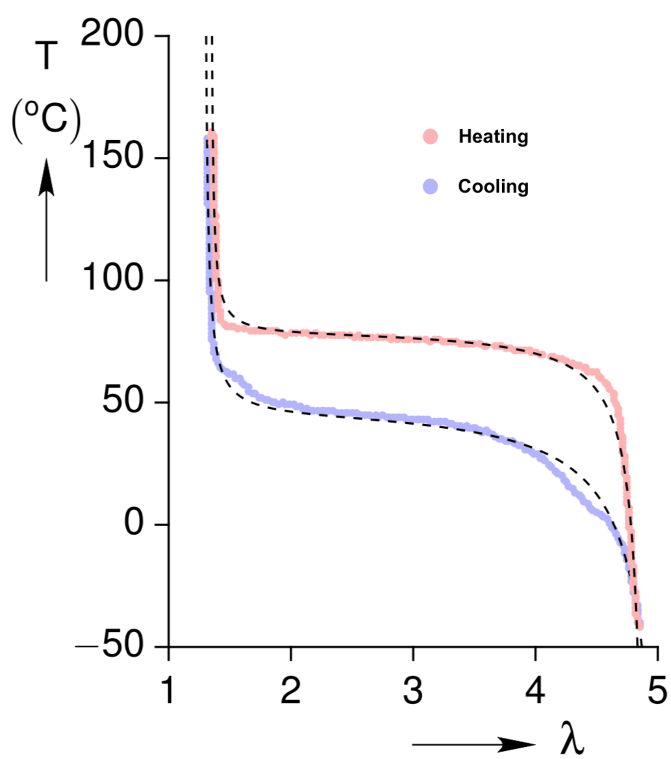


Figure 4.7: Experimental results and numerical fits for heating and cooling of 1 N load case.

Values of the fit parameters are shown in the resulting model in Figure 4.8, in which red is the heating parameter and blue corresponds to cooling. The values of T_0, T_1, and λ_I are clearly affected by the presence of R-phase at low load values. The non-monotonic behavior of the stretch ratios as load increases is reflected in the values of λ_M, which increase up to a load of 1 N, then decrease until the load reaches 1.75 N, and then increase again. The values of λ_M also capture the second decrease taking place between loads of 2 and 2.25 N, but the magnitude is small enough that it may be due to inconsistent behavior between samples, as shown in Section 4.3.1. Possible causes of the non-monotonic stretch behavior, described in Section 4.3.1 and Section 4.3.3, include the effects of R-phase and heat-treating methods.

4.3.5 Experimental Results of Thermal Cycling

A single test is performed to observe the shakedown that occurs between the first and second cycles on a virgin sample. The dead load value during this test is 1 N. The result is shown in Figure 4.9. We would expect thermal cycling to result in the typical shakedown behavior described in Section 1.1.5 that extends the spring's stretch [28, 33–35], but Figure 4.9 shows that the stretch ratio decreases on the second cycle (despite the occurrence of a small slip near the end of the martensitic transition that slightly increased the total stretch). Note that this cycling test was done at a load value of 1 N, which is the same value at which R-phase disappears and the overall stretch behavior begins to decrease in Figure 4.2. Gonzalez, Oliveira, and their colleagues also noticed this hardening behavior occurring with cycling at certain load values [19, 63]. It may be the case that thermal cycling results in stretch decrease rather than increase at load values at which R-phase is initially suppressed (see Section 4.3.3). This is investigated further during the discussion of thermal cycling of low-cycled springs (see Section 4.4.3).

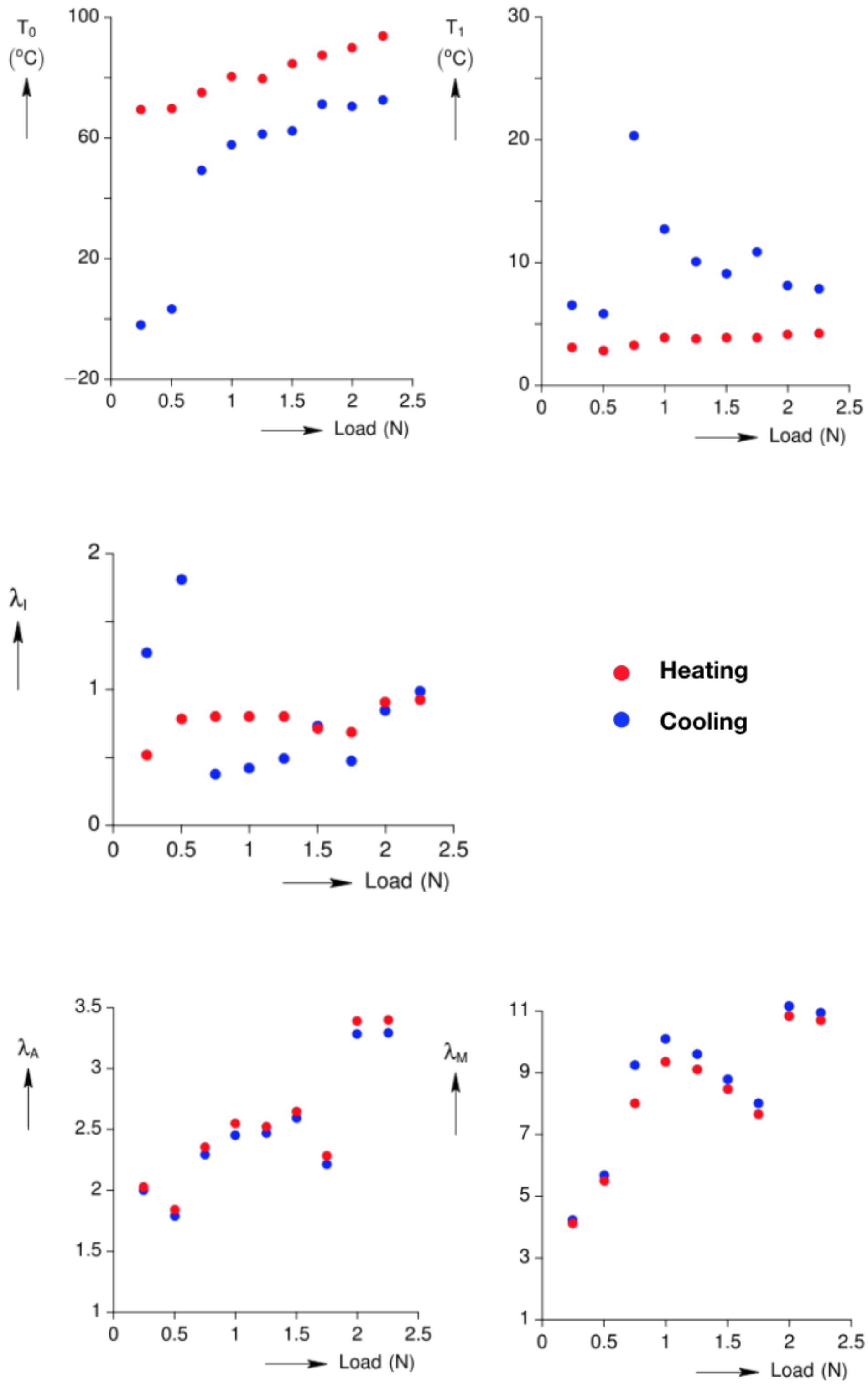


Figure 4.8: Numerical model derived from thermomechanical experimental results on virgin springs.

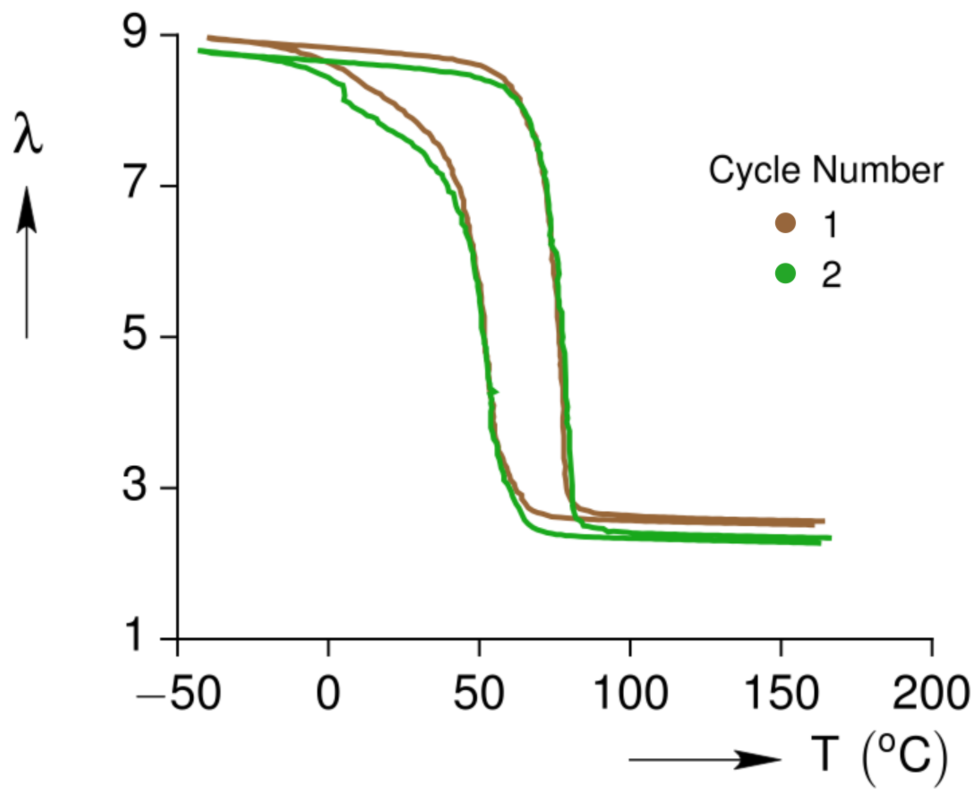


Figure 4.9: First and second cycles on a virgin sample at a load of 1 N.

4.4 Thermomechanical Experiments and Modeling of Low-Cycle SMA Springs

Experiments performed on cycled (also called "shaken-down") SMA springs allow for their confident use in applications that require repetitive actuation [36, 77, 78]. In this section, the thermomechanical testing and numerical analysis performed in Section 4.3 are repeated on a sample that has been thermally cycled on the order of tens of cycles.

4.4.1 Experimental Results of Load Variations

Thermomechanical tests are performed on a Dynalloy SMA tension spring with CS# 4608 [8]. This spring has a wire diameter d = 0.43 mm, a spring index of

$I = 5.06$, and an advertised transition temperature of 90°C. The sample contains 30 coils. It is mounted in the vertical experimental configuration as described in Section 2.4. The ends of the spring are coiled about a standard no. 2 set screw and held in place by a thin layer of high-temperature adhesive. One end of the sample is then clamped into a drill chuck near the bottom of the thermal chamber. The other end is secured into a homemade collet, to which the Kevlar thread is also attached. The spring thus has fixed-free boundary conditions, as can be seen in the photograph in Figure 4.10.

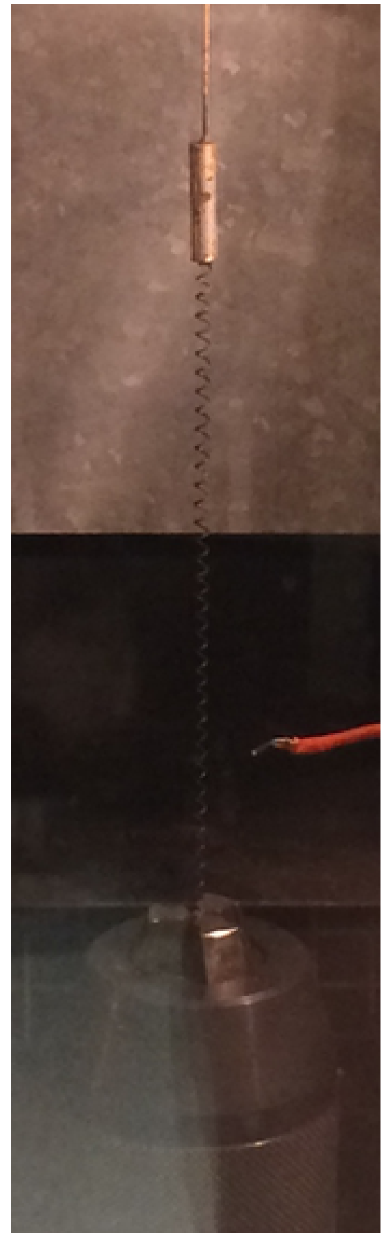


Figure 4.10: Photograph of a low-cycled spring sample mounted for thermomechanical testing.

The experimental procedure employed was described in Section 4.2, and the results for various constant load values are shown in Figure 4.11. Unlike in the case of the virgin spring samples described in Section 4.3.1, increasing the dead load value causes the stretch to increase monotonically; the non-monotonic behavior appears to have been "shaken out" of the spring. This finding is consistent with those in many published works [39, 58–60, 66]. Additionally, the R-phase transformation behavior seen at load values below 1 N with virgin spring (see Figure 4.2) is no longer present. It may be possible that the effects of R-phase decreased with repeated cycling, but this has not been reported experimentally in the literature. It seems more likely that the spring tested here has a different material composition than that tested in Section 4.3.1 (the two springs had similar geometry but different Dynalloy CS num-

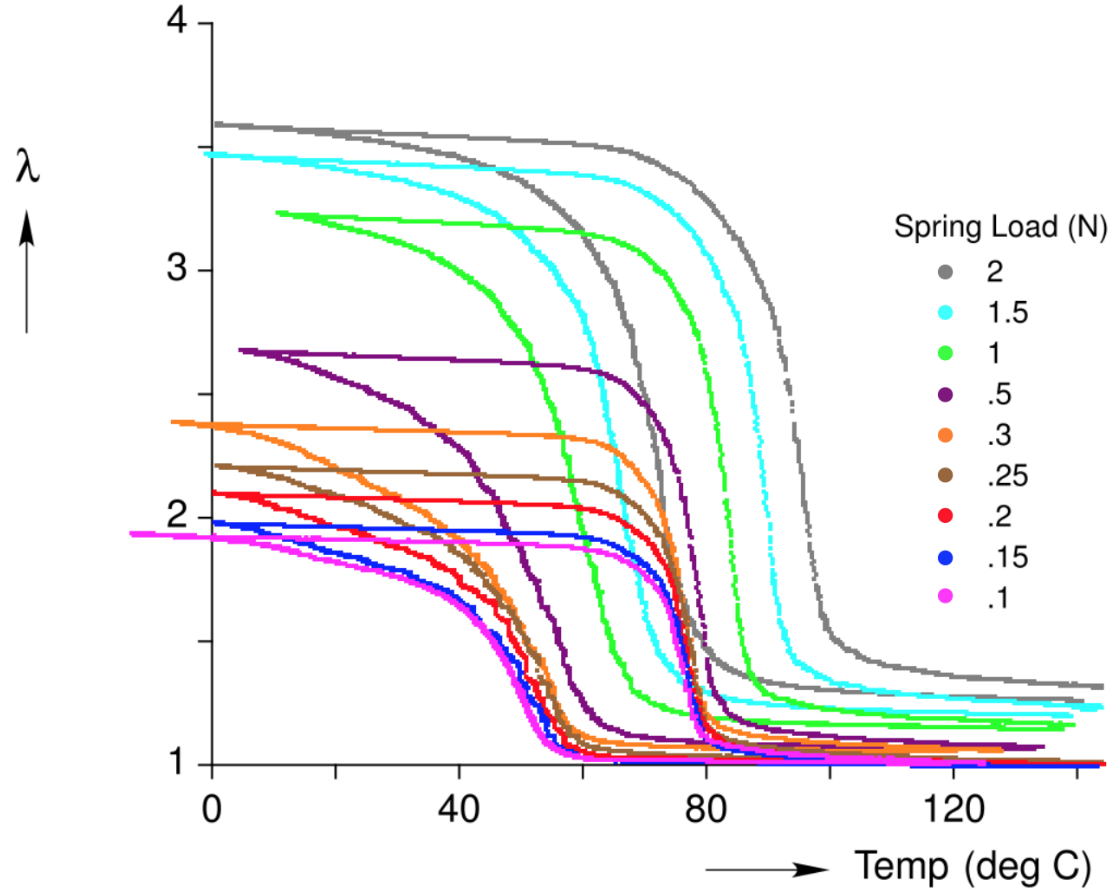


Figure 4.11: Thermomechanical experimental results on a low-cycled spring.

bers), and this SMA material does not undergo R-phase transformation [2]. In that case, it is possible that this spring in its virgin state may not have exhibited the "turn-around" behavior seen in Figure 4.2, if, as hypothesized, the decrease in stretch ratio at a certain range of load values was caused by the initial suppression of the R-phase (see Section 4.3.3). Alternatively, the two springs may have shape-set using different methods, as Oliveira et al. demonstrated that the length of heat treatment has an effect on the presence of R-phase within the thermomechanical experimental data [20].

4.4.2 Numerical Modeling of Load Variations

The same numerical modeling procedure that was described in Section 4.3.4 is applied to the thermomechanical results for the low-cycled spring sample. The results are shown in Figure 4.12. Compared to the virgin modeling results shown in Figure 4.8, the lack of R-phase transformation renders the model much more consistent at low load values. Additionally, the values of λ_M now increase monotonically with applied load value, as do the experimental results of resulting stretch.

4.4.3 Experimental Results of Thermal Cycling

Six of dead load tests shown in Figure 4.11 are repeated two more times each (with the exception of the 2 N load, which is repeated only once). The results are shown in Figure 4.13. For each load value, the darkest color is the first cycle and the lightest is the third. In the .1 N load case, cycling has little effect on the results. The .3 N and .5 N results illustrate the expected effects of shakedown [28, 33–35]: the spring decreases in overall stiffness as the stretch ratio increases with each successive cycle. Then, the 1 N case again shows little to no effects from cycling. The 1.5 and 2 N cases show the same hardening process previously seen in Figure 4.9, as the spring is seen to increase in stiffness. This phenomenon has been noted before by Gonzalez, et al. [19]. It may demonstrate an effect of R-phase transformations despite the lack of visible R-phase in the experimental data, which could be caused by different methods of heat treatment. Oliveira et al. found that the length of heat treatment had an effect on both the visibility of R-phase transformation within the experimental data as well as the presence and magnitude of the turn-around behavior [20]. It is therefore possible that the results in Figures 4.11 and 4.13 demonstrate the partially-stabilized response of a spring that has previously been thermally cycled, does not exhibit evidence of R-phase transformation austenite to martensite transformation at low load values, and yet still exhibits thermal-cycling-induced hardening at a particular range of load

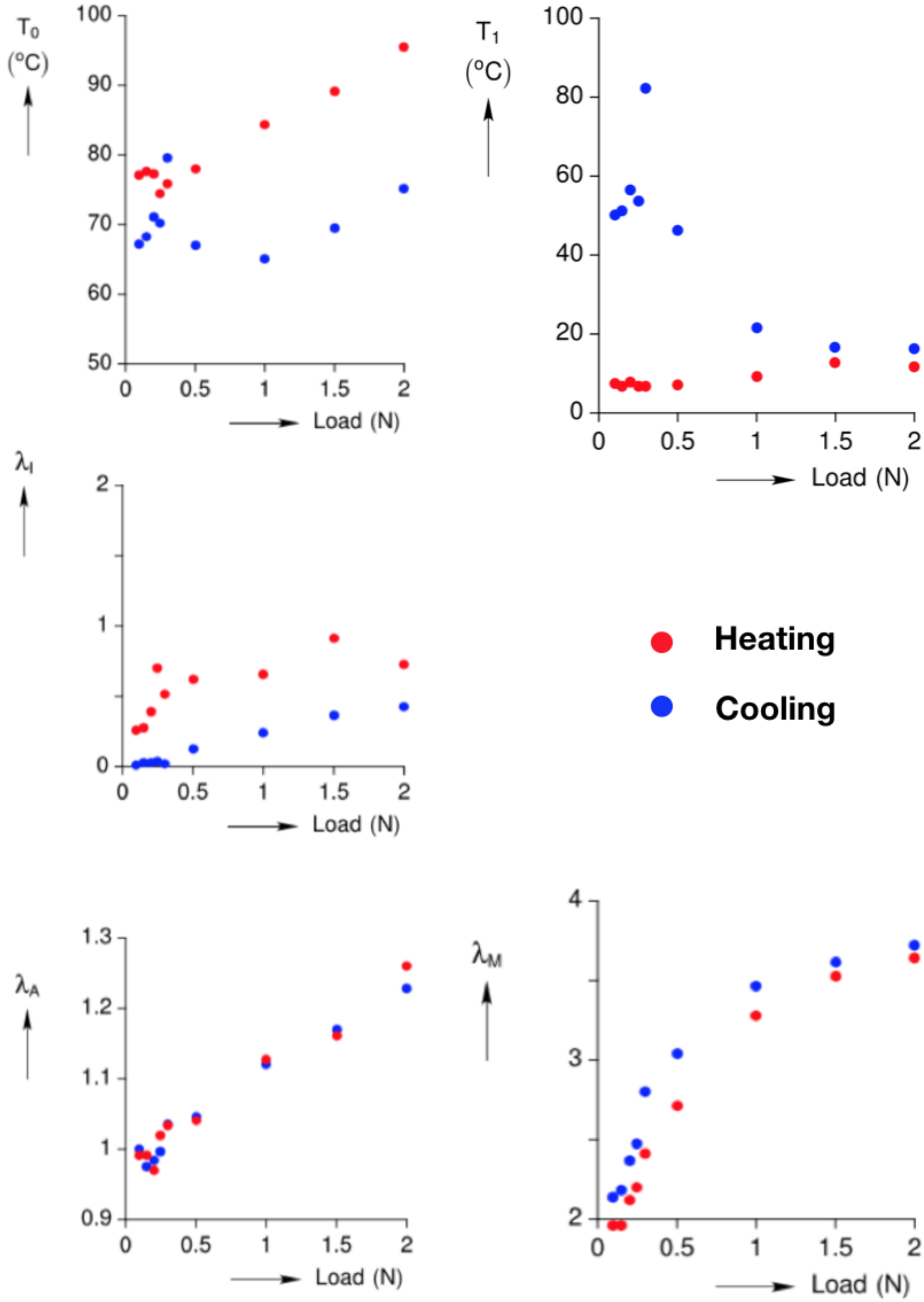


Figure 4.12: Numerical model derived from thermomechanical experimental results on a low-cycled spring.

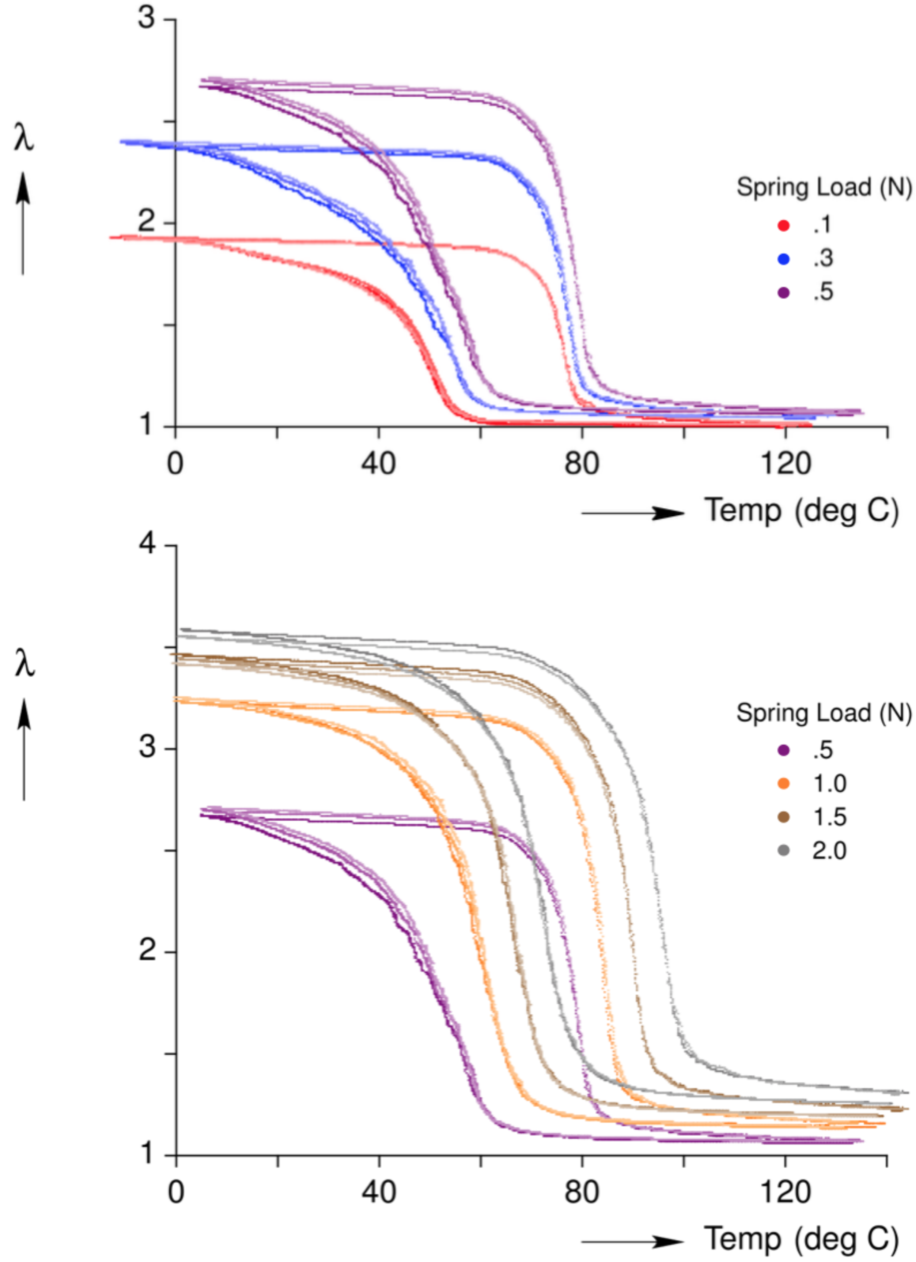


Figure 4.13: Cyclic thermomechanical experimental results on low-cycled spring samples (darkest colors are 1st cycle and lightest are 3rd).

values. Information about the various Dynalloy springs' material compositions and heat treatment processes would be necessary in order to determine the exact cause of this structural response.

4.4.4 Numerical Modeling of Thermal Cycling

The numerical model described in Section 4.3.4 is again applied, this time to the cyclic thermomechanical experimental results on the low-cycled spring. The 2 N load case is not modeled due to the lack of a third cycle. The resulting numerical model is shown in Figure 4.14. The darkest red and blue lines are the same model that was given in Figure 4.12. The lighter lines correspond to the next thermal cycle, and the lightest lines to the cycle after that. Cycling has the largest effect on the values of T_0, T_1 cooling, and λ_I heating; the remainder of the results do not appear to be significantly affected. It is difficult to identify where the hardening occurring in the 1.5 N case appears in the numerical model; additional cycles and load values above 1.5 N should be performed in order to draw further conclusions from this model.

4.5 Lifetime Thermomechanical Behavior of SMA Springs

As shown in Section 4.3, the virgin SMA springs behave in non-monotonic ways that are often difficult to predict. This is consistent with Stebner et al.'s claim that "few, if any, SMAs are capable of stable behavior in their virgin state" [36, p. 2108]. Section 4.4 analyzes a spring that behaves in a more predictable manner due to low levels of thermal cycling. As thermal cycling is increased, the behavior becomes even more stable, rending SMA springs effective for applications as actuators.

In one example of stable actuation behavior, Churchill tested a shaken-down SMA spring that was taken from a heat engine [58]. The sample had been cycled approximately 8,000 times, and the thermomechanical behavior is completely monotonic (increasing loads correspond to increasing stretch). In this chapter, I have applied

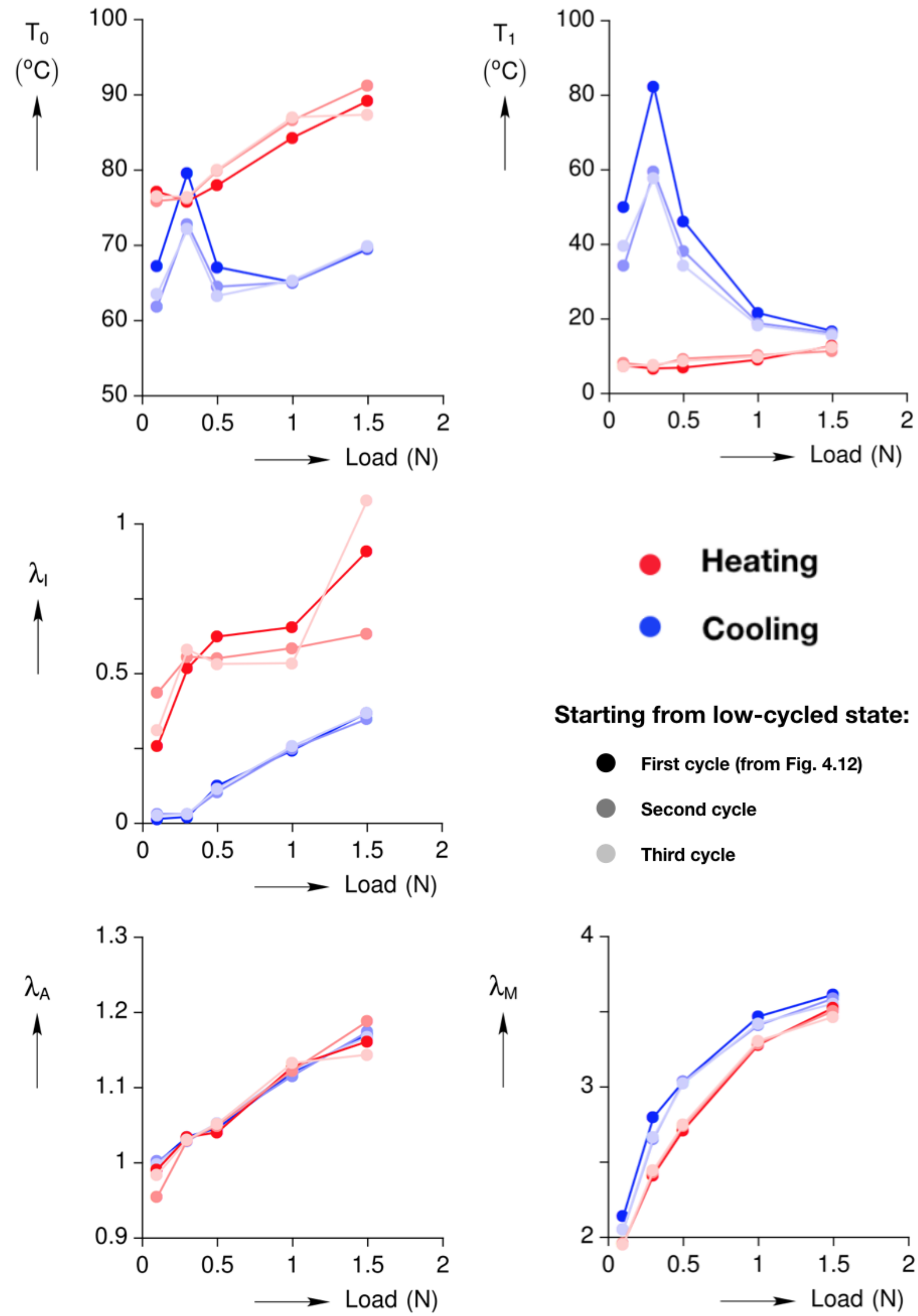


Figure 4.14: Numerical model derived from cyclic thermomechanical experimental results on low-cycled spring samples.

the numerical analysis procedure he developed for modeling the spring actuation behavior. Churchill's results show that the values of all five fit parameters increase upon increased load in both the heating and cooling cases. Churchill's fitting results are plotted with those presented in Sections 4.3.4 and 4.4.2 in Figure 4.15. Churchill's data was taken on a Dynalloy Flexinol® spring of very similar geometry; however, the austenitic transformation temperature was 30°C, and the boundary conditions were also different during testing. A comparison between the virgin and low-cycle experiments in this chapter and the high-cycle experiments performed by Churchill is shown in Table 4.1.

While the virgin spring model in Figure 4.8 shows non-monotonic behavior in nearly every parameter, Figure 4.12 on low-cycled springs shows that, with the exception of T_o cooling and T_1 cooling, the remainder of the parameters increase monotonically, as in [58]. This suggests that the low-cycled spring may be in middle of its "training" process and will obtain stable and consistent actuation performance with repeated further cycling. In addition, the outlying points caused by the presence of R-phase in the virgin sample do not appear in the low-shakedown model. Although the magnitudes of the parameters are expected to vary due to the difference in the thermal actuation temperature (see Table 4.1), in general it can be observed in Figure 4.15 that the low-cycling behavior occupies a middle ground between the erratic behavior of the virgin sample and the clean behavior of Churchill's high-cycled sample.

Table 4.1: Experimental differences in thermomechanical SMA spring results included in Figure 4.15.

Cycling	Author	Wire Dia.	Transformation Temp.	B.C.s	Load Range	Results
First	Bowen	.43 mm	90°C	Free-free	.25 - 2.25 N	Fig. 4.2
Tens	Bowen	.43 mm	90°C	Fixed-free	.1 - 2 N	Fig. 4.11
Thousands	Churchill	.30 mm	30°C	Fixed-fixed	.5 - 4.5 N	[58]

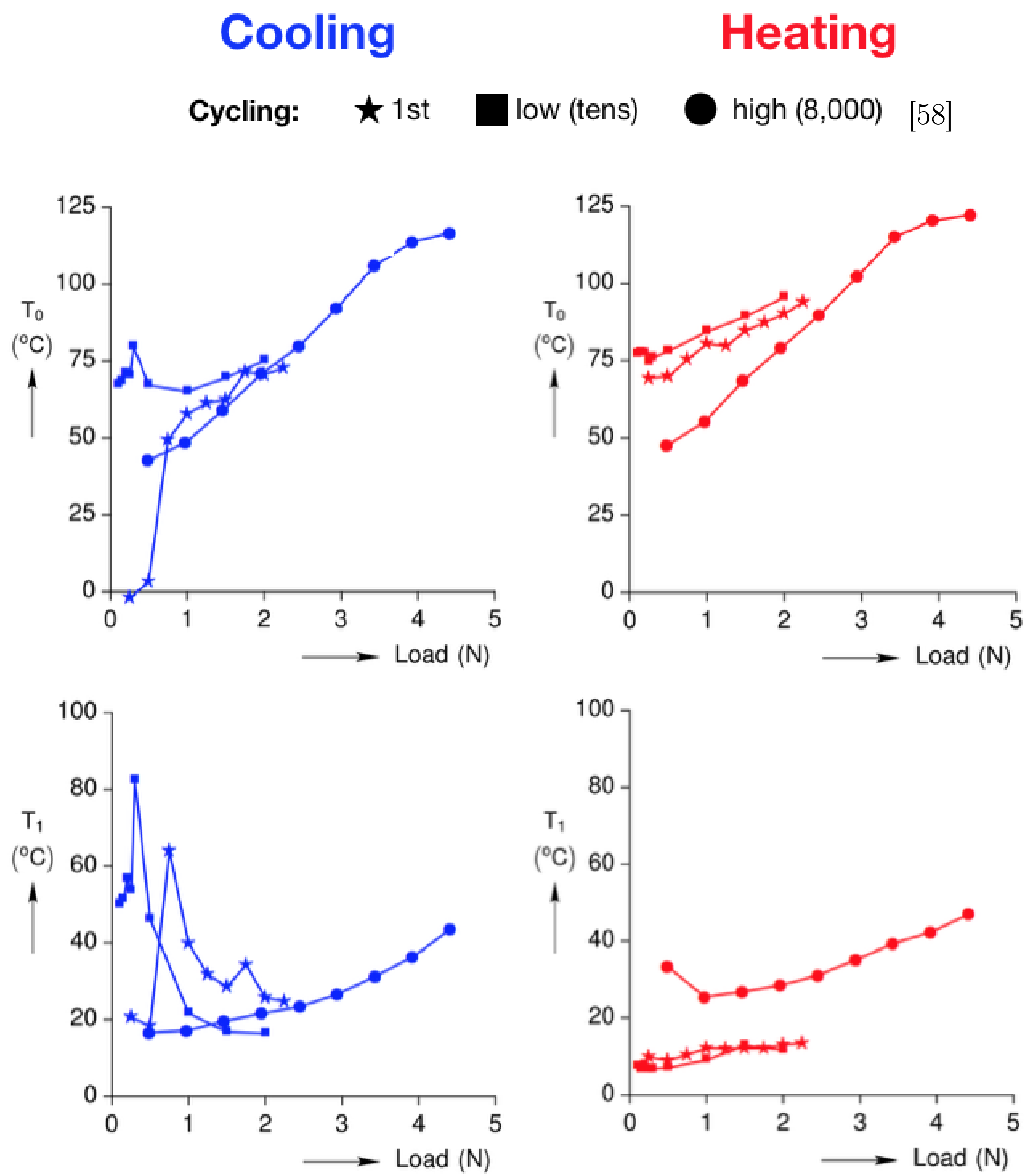
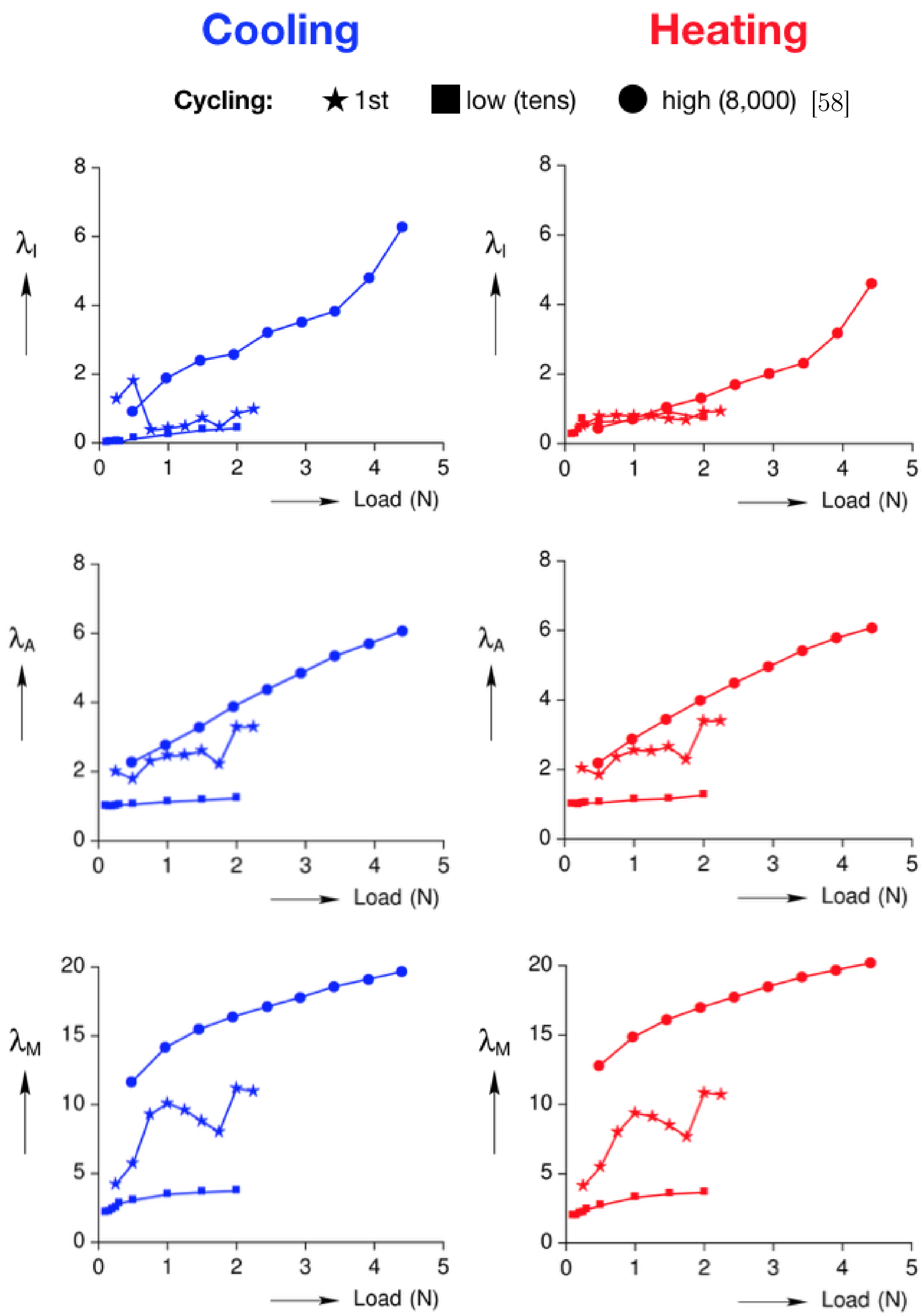


Figure 4.15: Numerical model of lifetime thermomechanical cycling results (data on high-cycled state from [58].



Cooling
Heating
Cycling:
1st
low (tens)
high (8,000) [58]
λI
λA
λM
Load (N)

4.6 Conclusion

In this chapter, I investigated the effects of thermal cycling on commercially-available SMA springs through both experiments and modeling efforts. The primary contribution of this work is experimental data on virgin samples demonstrating that material hardening occurs at loads just high enough to cause the suppression of R-phase transformation (see Section 4.2). I also applied Churchill's modeling technique to virgin and low-cycled spring samples, thus illustrating how stable, monotonic actuation behavior develops over the course of repeated thermal cycling. This work may have implications for material-level investigations into R-phase and the cycling process.

CHAPTER V

Conclusions and Future Work on SMA Springs

This part of the dissertation has tested and analyzed commercially-available Dynalloy Flexinol® shape memory alloy (SMA) helical springs for their isothermal and thermomechanical responses using a variety of geometrical, boundary, thermal, and mechanical loading conditions. The major contributions of the work can be summarized as follows:

- Incremental isothermal loading experiments in both martensite and austenite show the onset of plastic deformation at relatively low stretch ratios and spring loads.

- A rotational phenomenon is observed during isothermal and thermomechanical testing in which the end of a spring, if free to rotate, will change its direction of rotation during actuation.

- Martensitic isothermal experiments on low-cycle springs capture two distinct phases in the material before mechanical loading causes a transformation to detwinned martensite, only one of which appears to occur in virgin samples.

- An isothermal numerical modeling scheme is developed that aids in the documentation of isothermal behavior in general as well as the observation of two different martensitic behavior paradigms; which paradigm governs the spring behavior prior to detwinning is dependent on the temperature to which the material is cooled.

- High-resolution experimental data renders visible the twinned to detwinned martensitic transformation, marked by a sharp decrease in load during isothermal testing at the onset of the detwinning plateau.

- J2 elasto-plastic constitutive behavior is applied to mechanical spring loading using finite element simulation, and it is shown to be capable of capturing martensitic detwinning behavior.

- Thermomechanical experiments demonstrate a material hardening that occurs at constant load values just high enough to suppress the onset of R-phase transformation.

- Application of an existing numerical model to experimental data at various levels of cycling provides insight into the process by which stable actuation behavior develops over the course of repeated thermal cycling.

While this work draws attention to each of the above points, it is not a complete documentation of the stress-strain-temperature space for all material compositions, heat treatments, and geometries of SMA tension springs. The work outlined in the previous chapters could be continued using the following methods:

- Additional plastic deformation tests could be conducted and responses characterized as a function of spring geometry, material composition, and heat treatment parameters in order to determine the elastic limits of SMA actuators.

- Isothermal experiments could be performed at a wider range of temperatures to fully characterize the process of martensitic detwinning. Additional comparisons could also be made between various spring geometries, material compositions, heat treatment parameters, and cycling histories.

- To gain deeper understanding into the nature and magnitude of complex stress in the SMA springs, localized stresses and strains could be analyzed from J2-elasto-plastic finite element results. The Von Mises yield criteria could be replaced by Drucker-Prager in order to take in account the differences between tension and compression in yielding. A parametric study for various spring geometries could also be conducted using this material model.

- Thermomechanical experiments could be performed with small increments of constant load values over a larger range of loads in order to identify the cause of the drop in stretch with increasing load. To do so, a parametric study could compare the responses of springs of various geometries, material compositions, heat treatment parameters, and cycling histories.

This work could also be extended to include combinations of isothermal and thermomechanical actuation. As an example, I present preliminary results for the "box" test, in which thermal and mechanical loading are alternated. This test was previously performed by Biggs [86] on an SMA wire. I perform the same experiment using a low-cycled Dynalloy CS # 4726 spring sample, which also has an advertised transition temperature of 90°C. This spring has a spring index of 5.00 and a wire diameter of .43 mm. The spring sample is thermomechanically low-cycled and mounted in the thermal chamber with free-free boundary conditions (see Figure 5.1).

Figure 5.1: SMA spring sample prepped for the "box" test.

The results are shown in Figure 5.2. The "box" is controlled in the clockwise direction. The test begins with the sample hot (at 160°C) and unloaded (stage 1 in Figure 5.2). The sample is first cooled to -50°C (ending at stage 2). The prescribed load of 2 N is then applied via load control (ending at stage 3). The

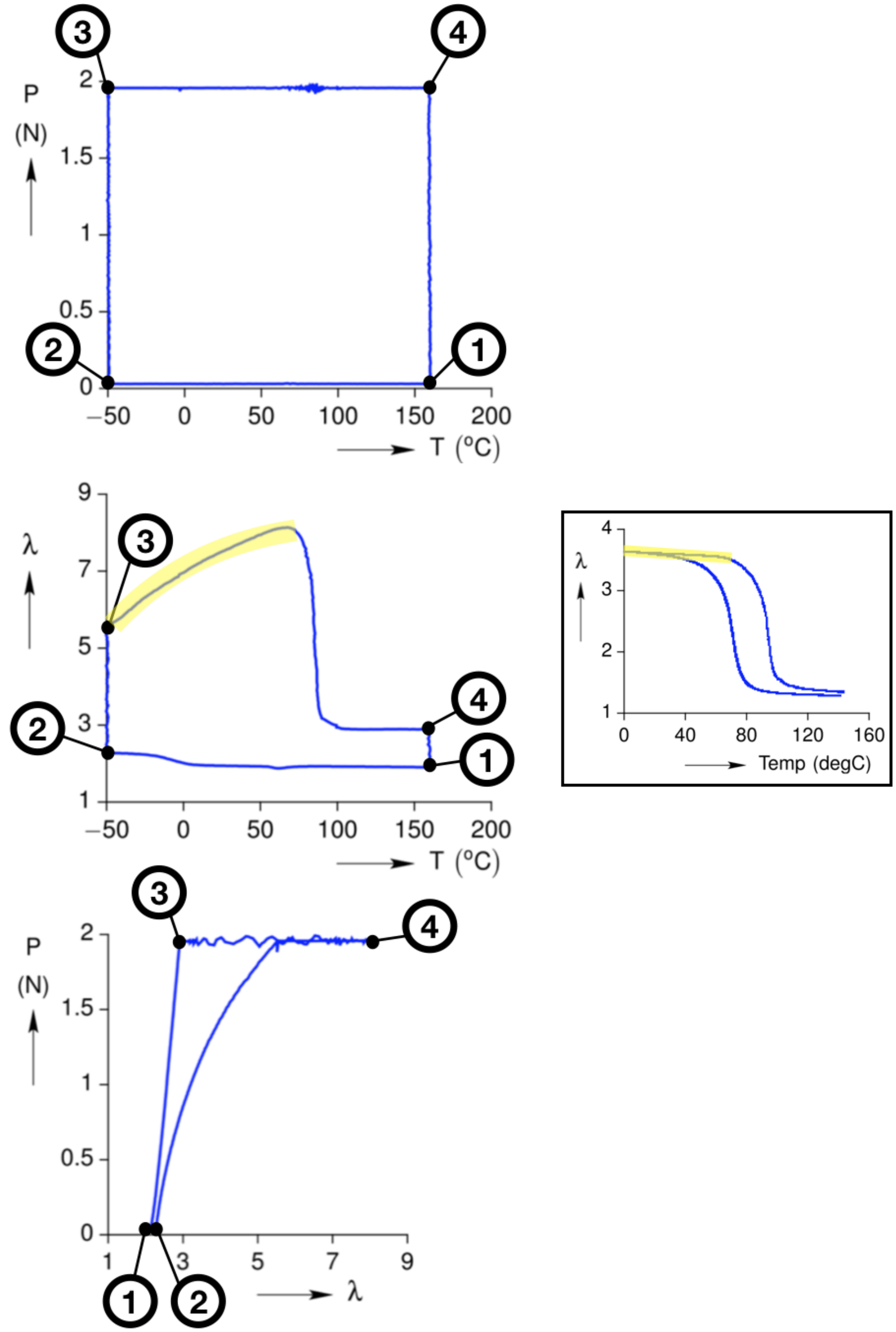


Figure 5.2: Thermomechanical "box" experimental results on a low-cycled spring sample (Inset: 2 N thermomechanical testing result from Figure 4.11).

sample is heated back to 160°C (ending at stage 4), and, finally, the load is released (ending back at stage 1).

Other than moderately tuned load control, the results are clean. An interesting feature is that, during heating from -50°C to the austenitic transition temperature (starting at stage 3), the spring continues to stretch, although the load is held constant (see the yellow highlighted section). This does seem logical, since the spring is in its martensitic state. With every increment that the spring stretches, it maintains its shape without any further applied load. Thus, in order to maintain a constant positive load, the spring must keep continually stretching. Note, however, that this does not occur in the constant load experiments presented in Chapter IV; the 2 N load case from the low-cycling experiments is shown in the inset in Figure 5.2 and the corresponding section is highlighted. The notable difference between these two experiments is that the load was applied while the spring was in austenite (prior to cooling) during thermomechanical testing, whereas the spring was already cooled to martensite when the load was applied during the box test. While it is not yet understood why this difference affects the spring response so drastically, the box experiment provides an example of the importance of performing new combinations of tests as we continue to expand our knowledge of spring structures and SMA materials.

SMA spring actuators, like other "smart" materials, have many current uses and enormous potential for applications in many industries. Effective technological innovation is dependent on rigorous scientific analyses that enhance both confidence in current applications as well as breadth of ideation for future ones. This thesis results in a forward step in our collective knowledge of SMA springs and will combine with future research within the field to enable even more significant contributions.

PART B: Critical and Liberative Analyses of Engineering Educational Systems

CHAPTER VI

Introduction to Critical and Liberative Theories in Engineering

> "There is, and there always has been, a dialectical relationship among education, politics, and power." - Ana Maria Araújo Freire [88, p. xv]

In this part of the thesis, I turn to the analysis of engineering education to address a number of questions. Who accesses it? Who completes it? What barriers prevent access and/or completion? What is it even about: what is it designed to do, for who, and why? Who decides? And, importantly, *how does it change?*

These questions are considered at the systemic level and from critical and liberative perspectives that acknowledge the roles of power relations within society [87, 89–94]. In this Chapter, I provide background on established critical and liberative frameworks and describe their potential uses within engineering education; I will apply these frameworks in theoretical, quantitative, and qualitative analyses in the following chapters. Chapter VII offers theoretical contributions in the form of model development, both relating the theoretical frameworks in general and demonstrating an example of theory development for engineering academia. Data-based analyses are then performed relating to the experiences and outcomes of marginalized undergraduate engineering students; quantitative analyses are undertaken in Chapter VIII, which investigate the question of who experiences success in engineering academia, and Chapter IX uses qualitative methods to identify the mechanisms through which this occurs. Chapter X concludes this part of the thesis with a summary of findings and recommendations for future work dedicated to the task of building an equitable and socially just model of engineering education.

Within Chapter VI, Section 6.1 describes critical theory in general and explains why, contrary to mainstream Western belief, capitalism is an inherently oppressive social system. Section 6.2 focuses the discussion on educational systems in particular. Finally, Section 6.3 describes the current state of research into engineering academic systems from the perspective of critical theory.

6.1 The Framework of Critical Theory

In this section, I describe some of the foundational tenants of critical theory, which calls to dismantle systems of capitalist oppression. I approach this broad topic from a Freirean perspective [87] and describe how the modern context of increased technology and globalization contributes to the capitalist exploitation of working class people. Understanding this process is an important first step to approaching and teaching engineering in a way that addresses structural oppression, including oppression on the basis of social class.

6.1.1 Capital and Society

In "Teaching Against Globalization and the New Imperialism: Toward a Revolutionary Pedagogy," McLaren and Farahmandpur [95] attribute the root cause of global income inequality to be the poor distribution of capital throughout our societies. Capital takes a number of forms, but monetary forms are of paramount importance to individual quality of life. Consumption capital is moneys which are earned in exchange for labor provided; one can think of it as wages [96]. Investment capital is a surplus of moneys that are invested in order to produce additional capital in the form of interest. Thus, an abundance of moneys above and beyond what is required to sustain life are required in order to obtain any amount of investment capital.

How various forms of capital are distributed is regulated by society [95]. Economic production results in capital, and people with similar relationships to the means of production are said to be of the same social class. Thus, two examples of social classes are workers, who directly sell their labor in exchange for consumption capital, and institutional owners, who receive the profits of production for use as investment capital. Because individuals with high class status maintain control of institutions as well as vast amounts of capital, they are able to preserve conditions that ensure the longevity of their own success while limiting opportunities for those outside of their social class [88, 97]. As Parenti explains, all social structures are defined by the ruling class:

> "There are class interests involved in how the law is written and enforced, how political leaders pursue issues, how science and social science are studied and funded, how work is done, how a university is ruled, how the news is reported, how mass culture is created and manipulated, how careers are advanced or retarded, how the environment is treated, how racism and sexism and activated and reinforced, and how social reality itself is defined" [97, p. 64].

6.1.2 Capitalism

Capitalism is a construct of society, not a naturally-occurring or self-sustaining entity, and its "engine ... is profit maximization and class struggle" [98, pp. 4-5]. The functionality of a capitalist system "... is predicated on the overaccumulation of capital and the super-exploitation of rank-and-file wage laborers" [95, p. 138]. The economic value of the labor produced by workers is more than that for which they are compensated, thus producing a surplus in labor value, called profit. This is the inherent contradiction of capitalism: for x labor, a worker is paid y capital, but their labor is actually worth z capital. To turn a profit, z must be greater than y. This is referred to by Marxists as the capitalist law of value (see Figure 6.1).

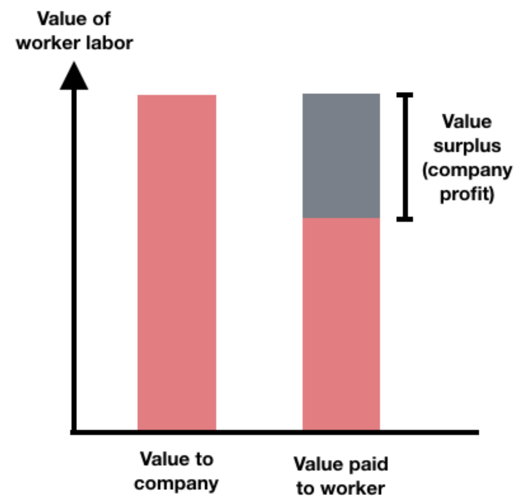


Figure 6.1: The capitalist law of value.

Through this process, as well as racist and sexist economic and social practices, unfettered capitalism results in the labor of millions of workers being exploited to generate profits for owners, who are members of the ruling class. The consumption capital consisting of workers' unpaid wages is accumulated by institutional owners and forms the basis of their wealth. Today, this wealth is the singular value of society on Earth as a whole. As the basis of economic analyses, wealth ignores morality, human needs, and social conscience, promoting a global culture focusing instead on money and consumerism [95].

Throughout this work, I will refrain from separating members of the so-called "middle class" from people living in poverty. This is purposeful. As is explained by critical theorists, it is in the interest of the ruling class to sustain the common belief that the oppression of the hegemonic class system is normal and unquestionable [87, 95, 99]. As such, it is beneficial for the ultra-wealthy ruling class that members of the middle class believe the explanation that poverty is a lifestyle choice resulting from laziness and ineptitude and that they can themselves join the ranks of the ultra-rich with effort and persistence. This belief convinces the middle class not to question the sanctity of a socioeconomic system in which "the richest 20 percent of the global population receive more than 80 percent of the global income" [100, p. 250]. Contrary to the meritocratic narrative benefiting the ruling class, members of the middle class have far more in common with people in poverty than they do with the wealthy. For this reason, I refer to the socioeconomically oppressed majority, comprising roughly 80 percent of the global population, as the working class.

Critical theory concludes that the modern combination of capitalism and globalization worldwide is resulting in further increases in global inequality [95]. It is common belief that, in light of globalization, national power can advocate for corporate interests but cannot save the middle class. This plays right into the hands of those who stand to benefit the most from this exploitive capitalist system. McLaren and Farahmandpur fittingly describe the plight of those who would offer opposition to the consolidation of corporate power: "...we are hard-pressed to chart out our daily struggles against oppression and exploitation instituted by a growing cabal of techno-crazed global robber barons" [95, p. 137].

6.2 Critical Theory in Education

> "No education is politically neutral." - bell hooks [89, p. 37]

This section considers the effects of capitalism on educational systems from a critical perspective. I explain why our educational system is inherently political and introduce the concept of critical pedagogy as a classroom-based intervention to support students who are not privileged under capitalism.

6.2.1 Education Under Capitalism

McLaren and Farahmandpur describe the process through which the combination of capitalism and globalization, in addition to increasing global inequality, also results in a decrease in educational quality for working class people [95]. In capitalist countries, the paradox of education becomes apparent as education is seen as the vessel that brings people out of poverty, but, at the same time, education is viewed as fuel for the capitalist economy [95, 101]. Both can't be true, because capitalism itself is locking people in structural oppression. Thus, our educational systems are actually reproducing the inequalities they are said to be fighting [95] (see Figure 6.2). For example, if the academic system was in fact a meritocracy, as is widely believed, excellent academic performance from the masses of the working class would achieve the extraordinary economic mobility purported to result from such excellence. However, this could not possibly be allowed to occur because doing so would destroy the national economy. This is because, in a capitalist society, most people must be workers, not owners. Our current beliefs about education under capitalism, therefore, contain a contradiction that is insurmountable for members of the working class.

Who, then, is able to succeed educationally within a capitalist system? McLaren and Farahmandpur explain that success " ... is not the result of individual capacities but rather is constrained and enabled by asymmetrical relations of power linked to race, class, gender, and sexual economies of privilege" [95, p. 146]. What knowledge is offered to students varies by class, gender, and race, holding them firmly in the same social status into which they were born. One common mechanism through which

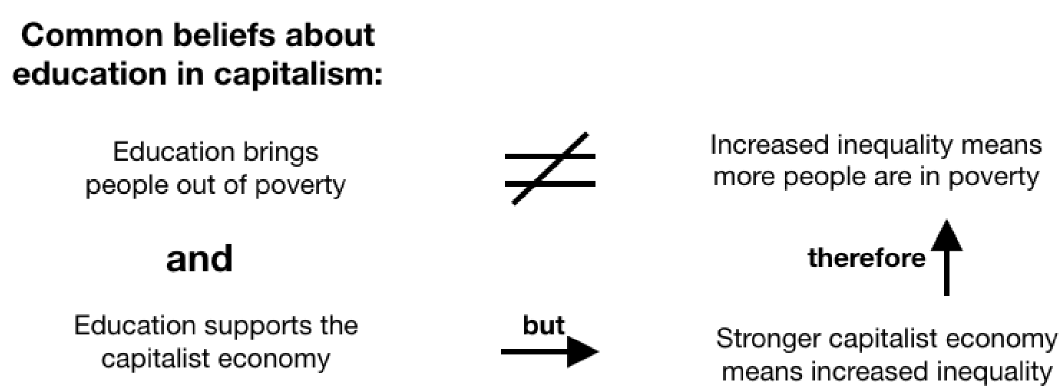


Figure 6.2: McLaren's critical theory of education (as described in [95])

this occurs is educational cost. While many countries have government programs intended to combat the exclusionary nature of education under capitalism, there are innumerous studies that document the failure of these programs to provide access to quality education for members of the working class [102–104]. Neoliberal initiatives have not and will not remedy the ills of capitalism, in education or on any other front.

6.2.2 Critical Pedagogy

The solution to cyclic oppression lies in a revolutionary approach to educational experience; in literature, this approach is referred to as revolutionary pedagogy, working class pedagogy, or critical pedagogy. This pedagogy is based on the work of Paulo Freire, who first described "education as the practice of freedom" in his seminal text *Pedagogy of the Oppressed* [87]. This text, originally published in 1970, scripted the liberation of working class people from the perspective of an educator. The aim of critical pedagogy is to encourage marginalized social groups to transform capitalist social and economic structures through an understanding of their role in the production process. In recognition of education's role in perpetuating oppressive systems, the classroom is used as a "political arena" for worker empowerment [95, p. 145]. Advocates for critical pedagogy call on educators to demonstrate a strong commitment to social justice as well as to promote networks that actively organize against capitalist structures [95, 105].

The accomplishment of these tasks is predicated on the development and use of language identifying the sources of oppression and exploitation [90, 95]. Current methods of discourse conceal power imbalances, favoring socially privileged classes and protecting the status quo [106]. Alternatively, educators must raise consciousness of class through opportunities for discovery; they must create the space to allow marginalized groups to share their realities with other students who may or may not be aware of the structural oppressions of capitalism [95, 107]. Additionally, through the understanding of the educational institution itself as an engine of the capitalist system, students should come to identify their own role as workers within the hegemonic structure of the institution [95, 108].

Within the context of classroom interactions, teachers and students must develop skills that McLaren and Farahmandpur refer to as critical literacy and critical consciousness [95]. Critical literacy is the ability to reflect on, analyze, and make judgements about political, social, and economic issues. To practice this, individuals should draw from their own lived social experiences and understandings. Through this discourse, they will then begin to build solidarity within the working class. The perspective that is developed as this occurs is termed critical consciousness. By stressing solidarity instead of differences, educators can start to combat the isolation that results from capitalist structures of production. Working in unity, the working classes can then begin to attack capitalist structures through mass organized political action. By removing the barriers that prevent students' realizations of structural oppression, teachers can help students develop their critical consciousness into the revolutionary consciousness that the working class needs in order to combat these oppressive systems.

6.3 Critical Theory in Engineering Education

Now that I have established a framework for the application of critical theory in education, I further tailor the discussion specifically to the area of engineering education. I explain how traditional engineering pedagogies are amplifying inequities that plague marginalized students. In presenting alternative pedagogical approaches, including critical pedagogy, I also introduce liberative and other identity-based frameworks, develop a model to help educators visualize the scopes of the frameworks, and provide examples of their uses in engineering classrooms.

6.3.1 Traditional Pedagogy in Engineering

"Traditional engineering education has been so widely understood to be inadequate that it has become cliché: 'from professor's notes to student's notes and through the minds of neither'" [109, p. 139]. The typical engineering educator views teaching as a simple transmission of information and perspective. This creates a massive power differential in the classroom, but the educator is as ignorant of this as they are of the effects of race, class, and gender [87, 109]. Students who experience this mindless style of pedagogy go on to practice it in their own classrooms; thus, Riley concludes that "...bad pedagogy [is] a rite of passage" in engineering [109, p. 141].

The teacher-centered teaching methodology commonplace in engineering education is a means by which teachers hope to maintain absolute control [109]. Educators also implement reductionist curriculum structure as a way to further control the transmission of content in the classroom. Within a reductionist structure, content is broken down into what is perceived to be manageable pieces and educators supply material, supervision, and feedback for each piece [109, 110]; this has also been referred to as the "factory model" [111]. This dissuades students from thinking critically and making interdisciplinary connections. Freire argues that this is a purposely executed technique – if they did so, students might grow to challenge the system that is so beneficial to the oppressors [87, 109]. Educators also often cling to the belief that engineering is objective, failing to recognize how social biases manifest within the material and influence students' educational experiences.

6.3.2 Liberative Pedagogies in Engineering

In her qualitative research study, "Employing Liberative Pedagogies in Engineering Education," Donna Riley describes an alternative and revolutionary approach to teaching in engineering [109]. Riley applies a liberative pedagogical framework to the field of engineering and specifically to an undergraduate thermodynamics course for which she was the instructor. She suggests teaching methods for use in engineering classrooms and provides examples of these methods as she employed them within the course. These methods include learner-centered methodology (see also [89]); problem and example selections that are relatable to diverse groups of students (including women); cooperative pedagogy (for example, paired examinations); circular seating; the incorporation of discussions of ethics and policy; and emphasis on the contributions of non-western, women, and minority scientists to the field, including candid discussion of the social and political circumstances that often prevented oppressed peoples from contributing and/or buried their contributions. This work is a helpful resource, as it provides concrete examples of classroom interventions designed to meet the goals of critical and liberative pedagogies.

Liberative pedagogy underscores the roles of privilege and power in all educational settings and work to address them through purposeful discourse and student empowerment [87]. Implicit, as well as explicit, bias is ever present in engineering classrooms, and teachers must confront these biases in both themselves and their peers in order to adequately support their marginalized students [109]. For example, textbooks (as well as teachers) frequently refer to engineers with he/him/his pronouns. It is imperative not only to avoid the use of biased tropes but also to address them openly in the classroom, so engineering teachers must be able to hold critical conversations on race, class, culture, and systems of oppression. Underrepresented students rely on these conversations to learn how to address discriminatory behavior as they encounter it, and students who are not underrepresented use them to develop the critical consciousness to stand with their underrepresented classmates in solidarity. These conversations plant the seeds of change as students begin to pursue critical discourse that combats oppression at all levels of society.

6.3.3 Liberative Theories in Engineering

Liberative Theory

Liberative pedagogy, as it is employed by Riley [109], aims to support *all* marginalized students, not just those coming from the working class majority. The theory of liberation, or liberative theory, thus encompasses all aspects of identity around which the structural hierarchies of society are organized [112, 113]. Through the wielding of hegemonic power, dominant groups are able to manipulate structures, conditions, and beliefs within society in order to further attain power and build their privilege. Dominant identity groups exist in relation to a potentially infinite number of attributes, and oppressive ideologies work to further the interests of the dominant group at the expense of others. The theory of liberation seeks to dismantle the many layers of systematic oppression that stifle the progress of marginalized peoples on the basis of any and all of these and other socially-constructed attributes.

Critical Theory

Alternatively, theories exist under the metaphorical umbrella of liberative theories that focus on oppression on the basis of particular attributes of identity. One such theory is critical theory, based on social class, which was described in detail in Section 6.1. I choose to emphasize critical theory within this thesis due in part to its problematic underuse in the engineering education research space, especially within the United States. However, there has been attention paid to other liberative theories in recent years, particularly the theories described below.

Feminist Theory

With a focus on the social construction of gender, the anti-oppressive branch of feminist theory aims to dismantle androcentrism and patriarchal structures within society, thus achieving the liberation of women [114, 115]. Kacey Beddoes has done extensive research documenting the use of feminist theories within the engineering education research space [115–117].

Critical Race Theory

Critical race theorists oppose incremental measures attempting to correct for racial discrimination in favor of structural and educational initiatives addressing systematic racism against people of color [91, 92]. Research in engineering education is beginning to make use of critical race frameworks to analyze the experiences of students of color and call for the formation of anti-racist engineering education [118, 119].

Intersectionality

The theory of intersectionality postulates that particular individuals will be overlooked by any theory that focuses on a single identity-based attribute; alternatively, combinations of attributes must also be considered in order to achieve liberation for all people [93, 94]. This framework was pioneered by Kimberlé Crenshaw as a means of understanding the compounding effects of discrimination against Black women on the bases of both gender and race. Intersectionality is more frequently being applied in engineering education research in recent years (see, for example, [120–122]). I apply an intersectional analysis framework Chapters VIII and IX to evaluate the outcomes and experiences of multi-marginalized students.

The educational research in the remainder of this thesis will be approached from the perspective of these critical and liberative theories. The relations between these theories will be addressed in more detail in Chapter VII and the studies described in Chapters VIII and IX provide examples of the use of these frameworks to study engineering educational systems.

CHAPTER VII

Modeling Critical and Liberative Theories in Engineering and Engineering Education

Chapter VI introduced the central concepts of critical and liberative educational theories; in this chapter, I build on these existing theories. In Section 7.1, I present a model relating these and other identity-based theories based on their scopes and goals. Then, Section 7.2 shows an example of the application of critical theory to engineering educational systems. Such theoretical developments are a necessary precursor to bringing about productive changes in society [123].

7.1 Modeling Anti-Oppressive Frameworks in Engineering

Throughout the history of western education, engineering has been widely accepted as a trajectory suitable for white, cis, straight, affluent men. Implicit and explicit bias continues to plague efforts to diversify the profession. Through quantitative analyses and rigorous control of both curriculum and classroom, engineering educators are wont to believe that they can control the outcomes of the educational process [109]. This demonstrates a failure to recognize how individual privilege contributes to academic success and how systems of oppression continue to prevent inclusivity toward women and minorities in engineering education. Although academic institutions often recognize that certain groups are underrepresented within their programs, diversity programming designed to remedy the situation only serves to assimilate underrepresented students into the existing culture. This carries a clear implication that it is the underrepresented students who need to be "fixed," rather than the existing cultures, which are exclusive and hostile [109]. While these diversity programs are often shown to aid in retention in the short term, "we will never be successful in raising the number of traditionally underrepresented people in engineering by merely teaching them to mimic the thoughts and actions of the majority" [109, p. 142]. This is an important distinction because, as Freire explains, it, too, is purposeful: "the more the oppressed can be led to adapt to that situation, the more easily they can be dominated" [87, p. 74].

As Trytten, Lowe, and Walden explain in their examination of Asian American engineering student experiences [124], proportional representation does not guarantee inclusive culture. Oppressed peoples are not always minority populations, as is the case in capitalist societies, in which workers far outnumber owners. Trytten et al. employ a framework of critical cultural theory, which, similar to liberative theory, posits that structural oppression occurs on the basis of many manufactured societal constructions, including ethnicity and gender in addition to class; liberation, therefore, requires consideration of the experiences of all oppressed peoples [89, 109]. Within the field of engineering, the marginalized status of women, African Americans, Hispanics, Native Americans, and working class people corresponds to disproportionately low representation of these groups [125–127]. For Asian American men, however, overrepresentation has not spared them from ethnicity-based oppression [124]. Further studies employing both critical and liberative theories may shed light on the realities experienced by members of various identity groups pursuing engineering education.

To aid in the framing of future research, I propose new models, shown in Figures 7.1 and 7.2, that situate the critical, liberative, and other oppression-based theories

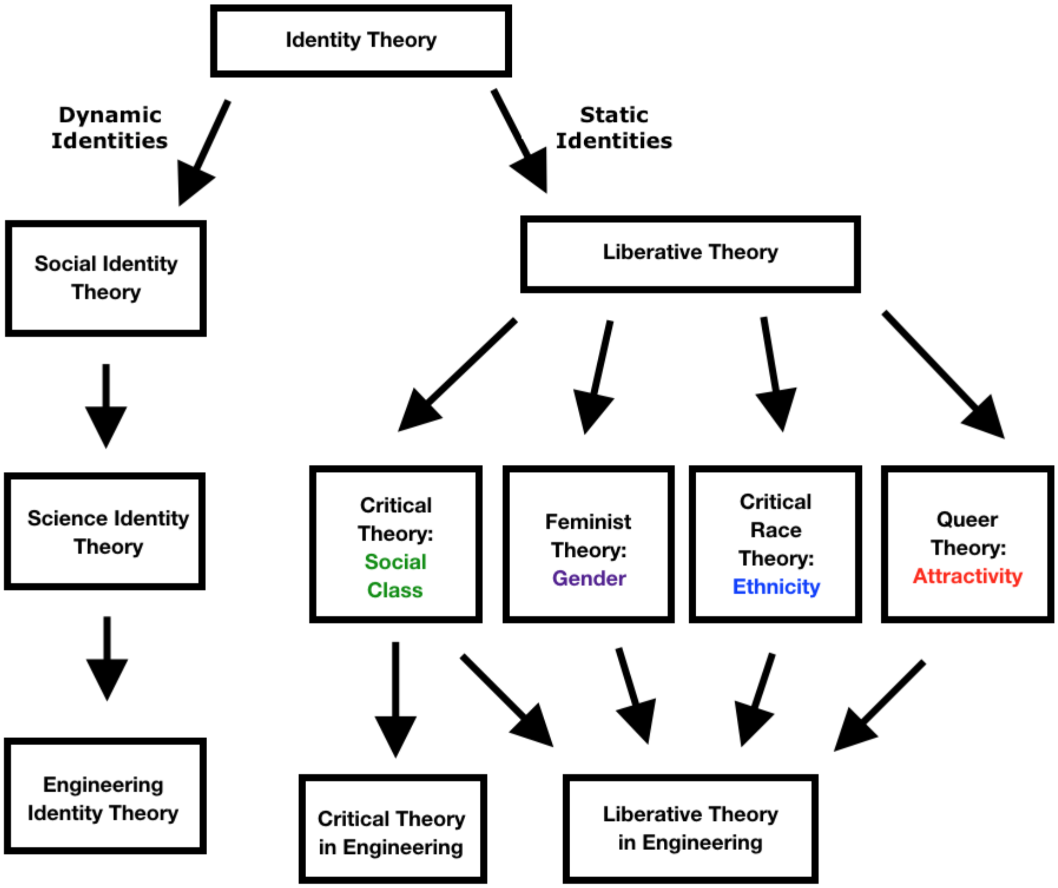


Figure 7.1: Model of relations between identity-based theories.

introduced in Chapter VI relative to one another within the broader classification of identity-based theories. Figure 7.1 demonstrates the relationship between anti-oppressive theories and engineering identity theory, which is more frequently applied in engineering education research. Engineering identity theories have tailored social identity theory to the development of identities that represent a feeling of belonging within engineering communities [128–130]. While social identity theory focuses on dynamic cognitive processes and perceptions that shape an individual's identity [131], liberative theory instead emphasizes the role of structural factors in presenting or withholding opportunities based on static aspects of identity [89, 109].

Under the metaphoric umbrella of liberative theory, other anti-oppressive theories

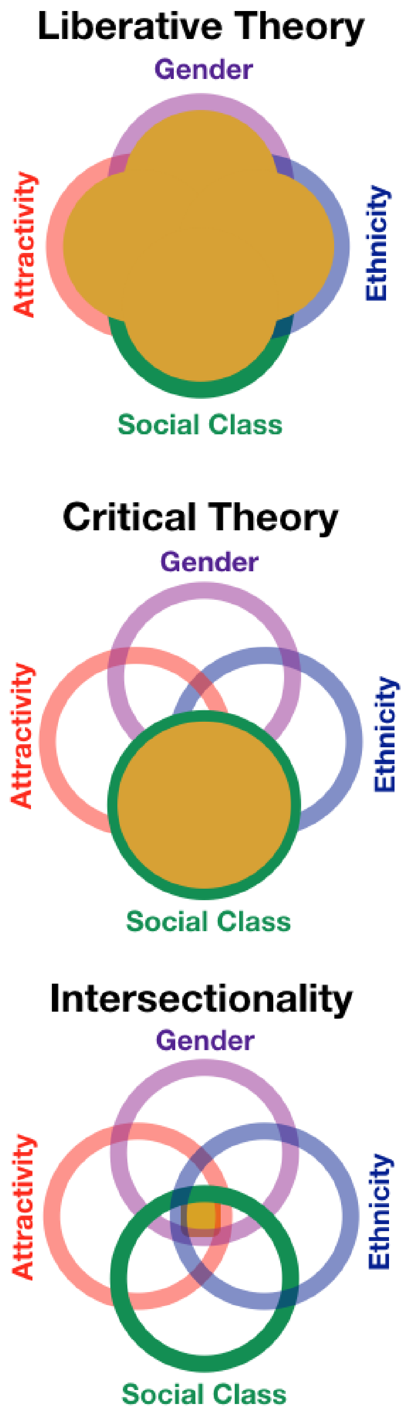


Figure 7.2: Model of relations between critical and liberative theories.

focus on specific attributes of marginalization. Critical theorists, such as McLaren and Farahmandpur, narrow the focus to socioeconomic status, posing that addressing the class struggle is the means through which we can bring an end to all forms of social oppression, since gender and race, like class, are in fact social constructs; thus, "... it is only through class politics that human liberation can truly be reached" [98, pp. 4-5]. Alternatively, theories exist that highlight oppression against marginalized groups based on gender, ethnicity, and attractivity, all of which have previously been applied to studies of engineering and engineers [118, 132, 133]. Liberative theory can encompass infinitely many aspects of identity and strives to achieve emancipation from all forms of oppression; Riley states that "no single pedagogy... will liberate all people" [109, p. 138].

Figure 7.2 shows the foci and scopes of the presented anti-oppressive theories. While critical theory, critical race theory, feminist theory, and queer theory each focus on a particular attribute of identity, the theory of intersectionality poses that *specific* combinations of marginalizations through various aspects of identity must be considered independently [93]. Alternatively, liberative theory considers all marginalized people concurrently, regardless of their specific marginalization. However, the ultimate aim of all liberative pedagogies are identical: to "collectively [create] democratic classrooms that encourage all voices" [109, p. 137] and ultimately dismantle the systems that lock people into oppressive realities. All of these theories, and their corresponding pedagogies, can and should be applied to engineering education. The next section is an example of one such application.

7.2 The Role of the Engineering Field in Western Capitalist Imperialism and Oppression

> "When machines and computers, profit motives and property rights are considered more important than people, the giant triplets of racism, materialism, and militarism are incapable of being conquered." - Martin Luther King, Jr. (April 4, 1967) [134]

7.2.1 Imperialism and Engineering

From a critical lens, it is imperative to recognize the role of imperialist militaries in both creating and perpetuating systems of oppression. Traditionally, imperialism has been recognized as the forceful domination of lands and peoples by powerful empires seeking colonial expansion. In modern society, as capital and political power have become increasingly concentrated, imperialism has taken other forms as well. The concept of globalization is used today as a façade for the imperialism imposed on developing nations through military intervention and financial maneuvers, resulting in further accumulation of capital for the ruling class [95]. These maneuvers are accepted by citizens of the offending nations on the basis that ceasing these behaviors would be extreme and radical – a direct result of the replacement of "imperialism" with "globalization" within our vocabulary. Meanwhile, the traditional definition of imperialism continues to bear relevance, although it is often disguised in the U.S. by language such as "acting in the national security," "protecting Americans," and "putting America first" [135]. While some Americans see through this façade, they are often themselves part of the working class labor force whose efforts directly enable the terrors brought upon victims of American foreign policy.

Engineers are guilty of playing a role in America's military imperialism [136]. The last century of Western history has seen incredible advancements in weapons technology through the efforts of engineers working for large industrial corporations [136, 137]. In addition to the systematic oppression that occurs through capitalism for the benefit of industrial owners at the expense of their workers, the fruits of workers' labor have been used to desecrate the very existence of marginalized global populations. Engineers at the German steel company, Krupp Industries, today a part of ThyssenKrupp, designed weapons for Nazi Germany during World War II, and the slave labor of Jews and other populations the Nazis deemed undesirable was used to power their manufacturing facilities [138]. From 1965 to 1969, engineers at Dow Chemical in Michigan produced the Napalm gel that burned civilians alive in Vietnam [139]; the famous photograph of civilian child victims is shown in Figure 7.3 [140]. Today, engineers at Raytheon design and produce weapons for the patronage of the government of Saudi Arabia; the Saudi government is using these weapons to commit genocide against the people of Yemen [141, 142]. As engineering educators, how many students from Yemen or of Yemeni descent do we teach in our classrooms? Are we handing our students the tools they'll be asked to use to murder their own people?

Figure 7.3: "The Terror of War" [140].

7.2.2 The Cycle of Western Capitalist Military-Based Imperialism

It is important to recognize that peaceful global relations are not in the interest of the ruling class in Western capitalist countries. By sustaining conflict-laden relations with foreign governments, the ruling class is able to maintain and/or increase national investment in the military industrial complex through a narrative of security and public safety. The investment has two primary products: weapons and profits, both of which are returned to the hands of the ruling class. Warfare persists, profits grow, and the cycle continues. The result is a highly lucrative industry; arms sales from the five biggest defense companies in the world – including U.S.-based Lockheed Martin, Boeing, Northrup Grumman, and Raytheon – totaled over 136 billion U.S. dollars in 2018 [143]. Additionally, a 2012 report found evidence that profit margins within the defense industry in the U.S. are "excessive" compared to those of other industries [144]. These profits constitute the true purpose of international conflict today. This circular process is shown in Figure 7.4.

To sustain for-profit military involvement over time, two necessary sources of fuel must be supplied: funding and labor. The ruling class provides some financial sup-

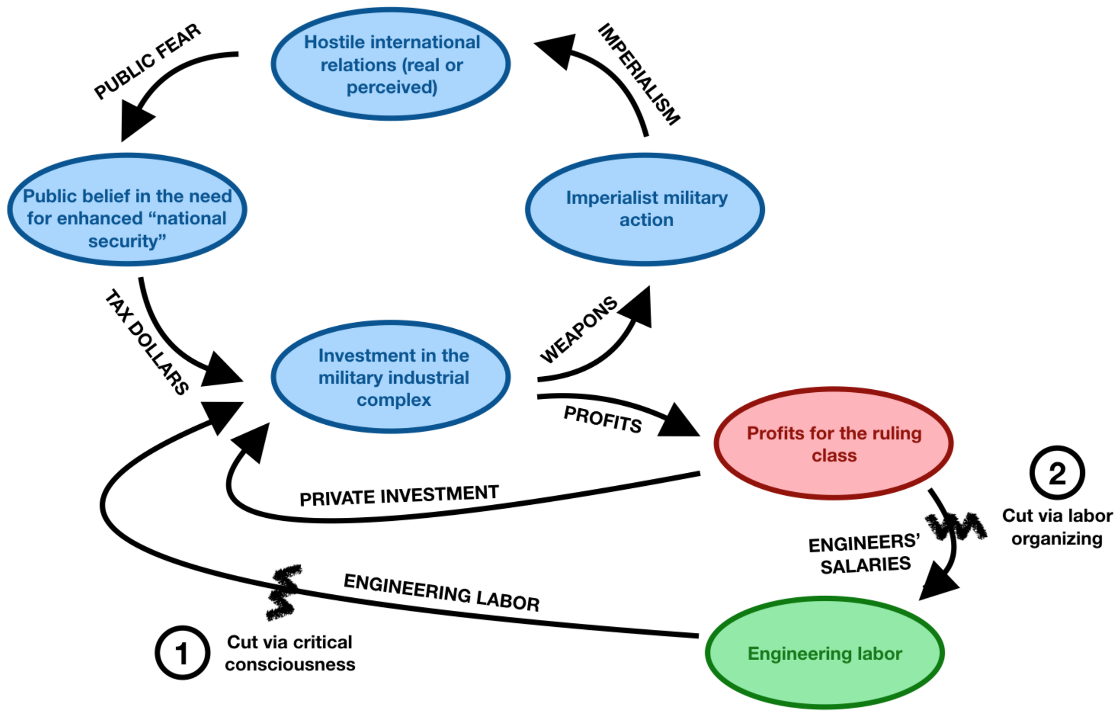


Figure 7.4: The modern cycle of Western capitalist military-based oppression.

port, but they cannot provide the necessary labor. Among those on whom they rely for labor are engineers – and they also rely on engineers' willingness to perform this labor. From the perspective of the engineer, the choice can appear straightforward; by performing this labor, the engineer is, according to the constructed narrative, increasing the safety and security of themselves, their families, and their country as a whole. Additionally, as engineers' pay is typically higher than that of other workers [145], they achieve financial security in a society with ever-increasing income inequality [146, 147]. An engineer's decision to withhold their labor from the military industrial complex can only occur through the deconstruction of the national security narrative and the economic option to forgo the pay. The former can be achieved through an understanding of the interests of the ruling class to maintain the cycle of capitalist international conflict; the latter, through labor organizing.

7.2.3 Step 1: Developing Critical Consciousness in Engineering Students

Far from adopting a critical perspective, traditional engineering education is viewed as entirely objective (see Section 6.3.1). The passivity of the student learning process in a lecture-focused classroom results in blunt memorization of content and procedure, a process Charles Reich describes as "mindless obedience training" [148, p. 139]. The lack of development of critical thinking skills prevents challenges to powerful entities, including military and industrial corporations, that directly benefit from engineering education through university research and the labor of engineering graduates [109, 148]. In contrast, educating the Western engineer with the interactive and equity-focused tactics of critical pedagogy (see Section 6.3.2) can provide the critical consciousness, as termed by Paulo Freire [87], necessary for them to recognize and reject their role in perpetuating oppressive hegemonic systems.

While ethics has recently become a more integral component of engineering education, engineering ethics is typically concerned with sustainability, communication, and legal matters [149–151]. Social justice, on the other hand, "... demands a deep and complex understanding of issues dealing with human power, social forces, justice, hegemony, human rights, and equality, all of which are seldom found ... in engineering programs or courses..." [151, p. 410]. In Nasser and Romanowski's study, the authors identified critical theory as the lens needed to reframe engineering education, concluding that engineering educators should "... give up their retreat into the myth of political or ethical neutrality based on the "science" of their work and confront their responsibility to ... teach students about social justice and encourage them to enter the struggle for a qualitatively better life for all" [p. 411]. While suggesting that engineering education shift from profiteering to designing for basic human needs, one faculty member in the study gave the example of a recent student project on low-cost bulletproof vests for civilians victimized by war. Both the faculty member as well as the study's authors failed to notice the irony that this engineering project's aim was to provide protection for victims of warfare enabled by technologies also designed by engineers. We cannot hope to change the priorities of engineering education until engineering educators possess the critical consciousness necessary to fully recognize the role their field plays in imperialism and oppression.

7.2.4 Step 2: Labor Organizing in Engineering Industry

Much of engineering employment in America today requires labor in support of the military industrial complex. In their 2008 study, Papadopoulos and Hable estimate that 8.8% of engineering labor is comprised of "defense-related activity" [152, p. 4]. Because many engineers perform this labor as only a small fraction of their total professional activities, estimates suggest that thirty to sixty percent of the U.S. engineering workforce is involved in military activity [152, 153]. Given this quantity of military efforts in engineering, how can we reasonably expect engineers to withhold their labor? Blue, Levine, and Nieusma state in *Engineering and war: Militarism, ethics, institutions, alternatives*, "disentangling engineering from militarism and war requires sustained, broad-based effort and cannot be achieved solely by variously motivated individuals opting out of military projects" [136, p. 18]. We can amend this statement to say: *disentangling engineering from militarism and war requires sustained, broad-based effort and <u>can</u> be achieved by <u>critically conscious individuals organizing within themselves</u> in order to <u>collectively abstain from participation</u> in military projects.*

Engineering has not historically been a primary setting of labor organizing. This may be due to the relative political conservatism of members of the field [154–156] and to the typically higher wages paid to engineers than to many other types of workers [145]. However, labor organizing in engineering is demonstrated in several successful past organizing campaigns, such as the 2000 strike of engineers and machinists at the Boeing Company [157]. Seventeen thousand workers held pickets (see Figures 7.5

and 7.6), and the company's shareholders pressured management into giving in to workers' demands after the strike caused Boeing stock to drop by 32 percent. Today, engineers at Ford are organizing within themselves to collectively stand against the use of their labor in the development of militarized police vehicles [158]. The state-sponsored violence against Black communities Ford's workers are protesting is an example of what Peter Mayo refers to as "internal colonization" [159]. By continuing to build collective power, engineers will be able to create circumstances in which they are protected while refusing to apply their skills and training to institutionalized oppression.

Figure 7.5: Boeing strike poster [160]

Figure 7.6: Workers on strike [161]

7.2.5 Engineering for the Common Good

In recognition of their role in perpetuating imperialism, engineers must join collectively to bring an end to the use of their labor for oppressive purposes. Engineering educators have a duty to not only examine the impacts of their own technical work from a critical perspective but to also employ the principles of critical pedagogies within their classrooms to produce a critically conscious generation of engineers who can meet the following goals:

- Recognize and vocalize the compounding effects of capitalism, technology, and the military industrial complex.
- Employ critical pedagogies within their classrooms.
- Organize within their localized communities and workspaces.
- Stand in solidarity with oppressed peoples by withholding their labor from destructive and oppressive projects.

Through this process, engineers must largely re-shape the very purpose of their field. In today's neoliberal, profit-driven world, it can be hard to imagine what *Engineering for the Common Good* might look like. In light of the intersecting developments of globalization and technological advancement, the focus of the engineering profession must be to provide access to infrastructure that meets fundamental human needs worldwide. Engineers must design and construct public health, transit, and utility infrastructure systems that contribute to the collective good of all people. It is within the power of the educator to transform the agenda of engineering education from the supremacy of profits to the empowerment of people.

CHAPTER VIII

Critical Quantitative Analyses of Engineering Educational Outcomes

I now turn to analyses regarding marginalized undergraduate engineering students at a large, highly-selective public university. In this chapter, I critically analyze quantitative outcomes with respect to demographics. Chapter IX will then utilize qualitative methods to describe and explain the trends found in this chapter. In conjunction, these chapters constitute a mixed-methods application of critical and liberative frameworks to the study of marginalized undergraduate engineering student populations.

8.1 Introduction

It has long been recognized that the representation rates of women and students of color in engineering lag behind the demographics of the U.S. population [125, 126, 162, 163]. Interventions at the institutional level increasingly seek to mitigate the problem through incremental measures addressing recruitment and retention of these students [109, 164]. In doing so, these institutions have begun to confront internal cultural biases that render their environments hostile toward marginalized students. While it is perhaps becoming more commonplace within engineering spaces to highlight our field's bias towards white men, the same level of awareness has not yet developed about the marginalization of engineering students who do not come from the upper reaches of the global socioeconomic strata [165]. In response, this study intends to bring students' access to financial capital, or lack thereof, into the conversation about diversity-related representation rates and student outcomes.

This study examines several measures of student performance and achievement in engineering undergraduate education at a large, doctoral-degree granting, research-oriented, highly selective public university in the Midwestern United States. The data, which was provided by the institution directly, consist of self-reported gender, ethnicity, and annual household income levels collected upon enrollment in conjunction with university-tracked records of each student's grade point average (GPA) and process towards degree completion. The data set includes students entering the engineering college between the Fall 2011 and Fall 2017 semesters. International students were excluded from the study in order to focus on the effects of societal processes within the United States. The research goals of this study, which are pursued through statistical analyses, were as follows:

- Provide institutional context by determining if the independent variables – 1) gender, 2) ethnicity, and 3) annual household income level – and the interactions between them demonstrate a reasonable representation of the United States population and/or the population of the state in which the university is located. If neither of the above is true, determine whether the underrepresented groups identified in existing engineering education literature are also underrepresented at this highly selective research institution.

- Investigate if and how the three independent variables and their interactions are related to the dependent variables – 1) success or failure to graduate with a Bachelor's degree in engineering, 2) time to graduation from initial enrollment, 3) and cumulative GPA at the fourth semester of study – at this institution.

After a review of existing related research, we present our findings on each of the topics sequentially. For each, we describe our research methods followed by a discussion of the results. We also compare our results to those of other studies, if applicable. The conclusion describes the implications of the results laid forth in this study as well as our intended future work in this area.

8.2 Review of Literature

The underrepresentation of women and students of color in engineering is a commonly understood and well-researched phenomenon [125, 126, 163, 166]. There are also a plethora of studies documenting the educational outcomes of undergraduate engineering students on the bases of gender and ethnicity [126, 127, 163, 166–176], the results of which will be compared to our findings throughout this paper. However, engineering education researchers are often wont to omit the effects of social class on educational opportunity and performance. In western countries, social class is largely defined by socioeconomic status. A few studies have examined the outcomes of engineering students on the basis of socioeconomic status [104, 171, 177, 178], and results will be compared where they are available. No studies could be located examining the grade point averages of engineering undergraduate students on the basis of socioeconomic status, although a few exist that study undergraduates regardless of major [179, 180].

It is important to recognize that income is not proportionally distributed across ethnic boundaries. Figure 8.1 shows the median incomes of households in the United States according to 2016 census data [181]. While a significant contribution of this study to existing literature is the extension of previous studies' bases of gender and ethnicity to include income, the inequitable distribution of income within our societies renders it prudent to examine the effects of interactions of income levels with gender and ethnicity in addition to the effects of income alone. Through these investigations,

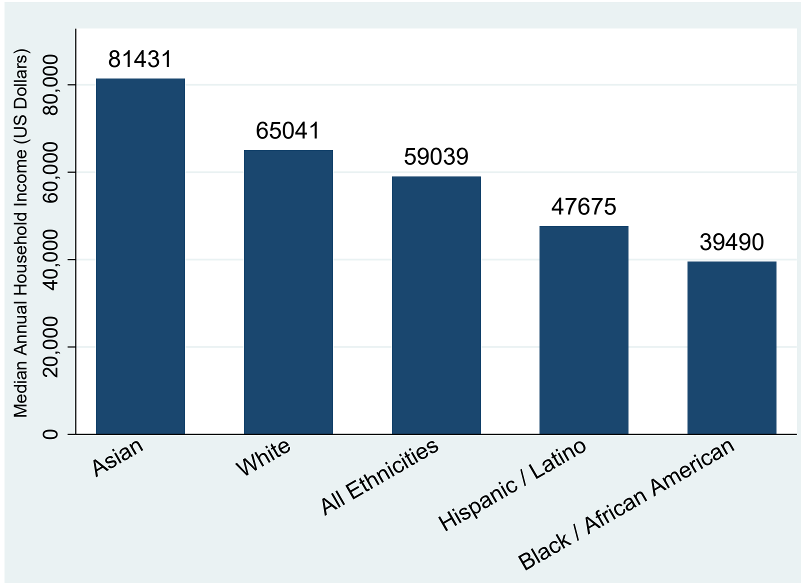


Figure 8.1: Median household income by ethnicity in the United States, 2016 [181].

we hope to develop a better understanding of the ways in which class-based oppression manifests itself within the space of engineering education.

8.3 Data

The data for this study was provided directly by the engineering college from their internal records on undergraduate student demographics, enrollment, and performance for the time span between the Fall 2011 and the Fall 2017 semesters. Gender, ethnicity, and income are treated as independent variables within this study. Gender is reported in the data as either man or woman, the only options the university provided to the students. Ethnicity choices presented included Asian (including the Indian Subcontinent and the Philippines), Black or African American (including Africa and the Caribbean), Hispanic or Latino, and white (including Middle Eastern). Students were able to select more than one ethnicity, so Two or More Ethnicities is also an ethnicity subgroup that was examined in this study. Students reporting their sole ethnicity to be American Indian, Alaska Native, Native Hawaiian, Pacific Islander, or any other Original Peoples were excluded from the study due to extremely low representation and the potential for the violation of confidentiality. However, if they also selected at least one other ethnicity, they were included in the Two or More Ethnicities subgroup. Students reported their estimated annual gross household income by selecting one of many ranges of incomes, which we then consolidated into five ranges: under \$50,000, \$50,000 - \$99,999, \$100,000 - \$149,999, \$150,000 - \$199,999, and \$200,000 or more in U.S. Dollars. Students who did not report one or more of their gender, ethnicity, and household income were omitted from the study. This left 7,621 student data points, which is 73.6% of the population of domestic students who entered the college between Fall 2011 and Fall 2017. The frequency counts of gender, ethnicity, and annual household income level are shown in Table 8.1.

8.4 Results

8.4.1 Representation Rates

The three independent variables (gender, ethnicity, and income) are tested for associations using chi-square analyses. Chi-square tests are also used to compare representation levels within subgroups to that in the United States and the state in which this university is located.

Women are extremely underrepresented in most engineering programs [125, 126, 162, 163], and the same is true at this engineering college. In comparing the proportion of students who were women to that of the populations of the country and state

Table 8.1: Frequency counts of gender, ethnicity, and annual household income level.

Annual Household	Asian		B / AA		H / L		Two or More		White	
Income	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
< \$50,000	180	69	46	25	96	27	34	15	382	125
\$50,000 - \$99,999	226	100	43	21	98	33	44	31	792	228
\$100,000 - \$149,999	301	104	27	11	73	29	57	20	880	308
\$150,000 - \$199,999	175	72	10	6	34	16	33	15	516	194
> \$200,000	286	94	20	9	83	29	69	27	1,065	443

(taken from the 2012 - 2016 American Community Survey 5-Year Data Profile by the U.S. Census Bureau), the discrepancy is extremely statistically significant with $p < 0.001$ [181]. The comparison is shown in Figure 8.2 (note that, in the figure, the last two columns refer to this engineering college). Notably, results from the National Postsecondary Student Aid Study (NPSAS), a project of the National Center for Education Statistics at the United States Department of Education, show that the average representation of women in undergraduate engineering and engineering technology programs at public four-year universities in the United States is only 20.7% [182]. By that figure, this engineering college is doing slightly better than the average engineering program.

In considering the representation rates of students of various ethnicities, Black / African American and Hispanic / Latino students were very underrepresented (see Figure 8.3, in which the last two columns refer to this engineering college). When comparing the ethnicity distribution of the engineering college starters to either state

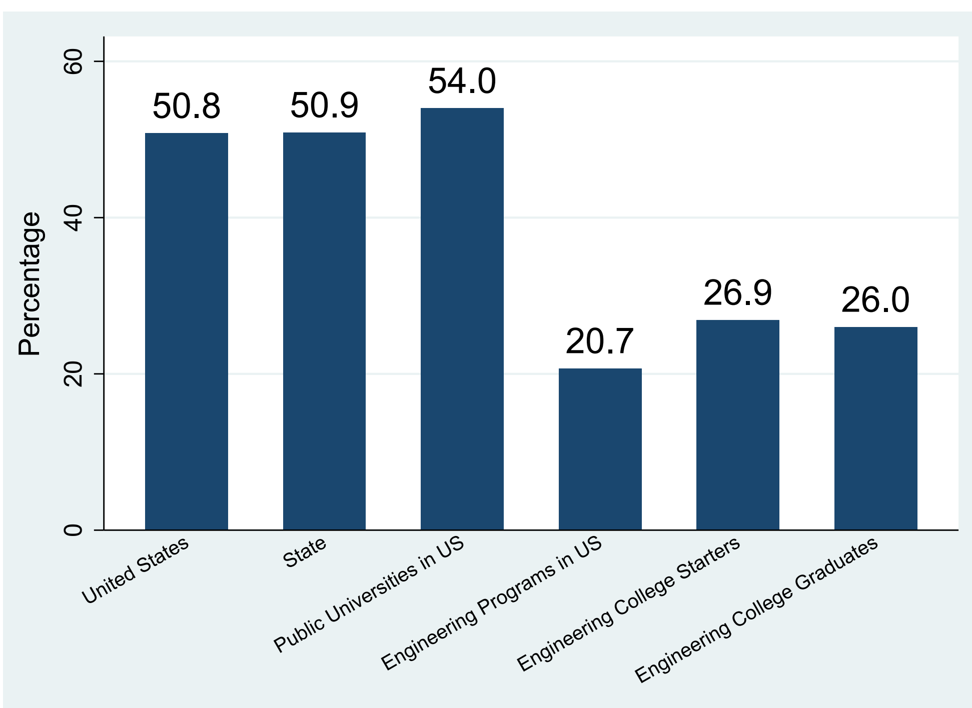


Figure 8.2: Percentage of women in populations [181, 182].

or national distributions, the results are very statistically significant, with $p < 0.001$ in both cases. The underrepresentation of students of color has been very well documented in existing literature [126, 127, 167–171, 174–176].

While women were underrepresented in all ethnicities at this institution, they were least underrepresented amongst Black / African American students, at 33.0%, and students who reported two or more ethnicities, at 31.3%. White students, in contrast, were only 26.3% women. While the correlation between gender and ethnicity had a p-level of $p = 0.065$, which is slightly above what is typically considered to be statistically significant [183], this finding is consistent with results reported in literature [126, 166].

Working class students were extremely underrepresented in our data. Since approximately seventy percent of the households in the United States fall into the income ranges of under $50,000 and $50,000 - $99,999 (see Figure 8.4, in which the last two columns refer to this engineering college), we define students in these cate-

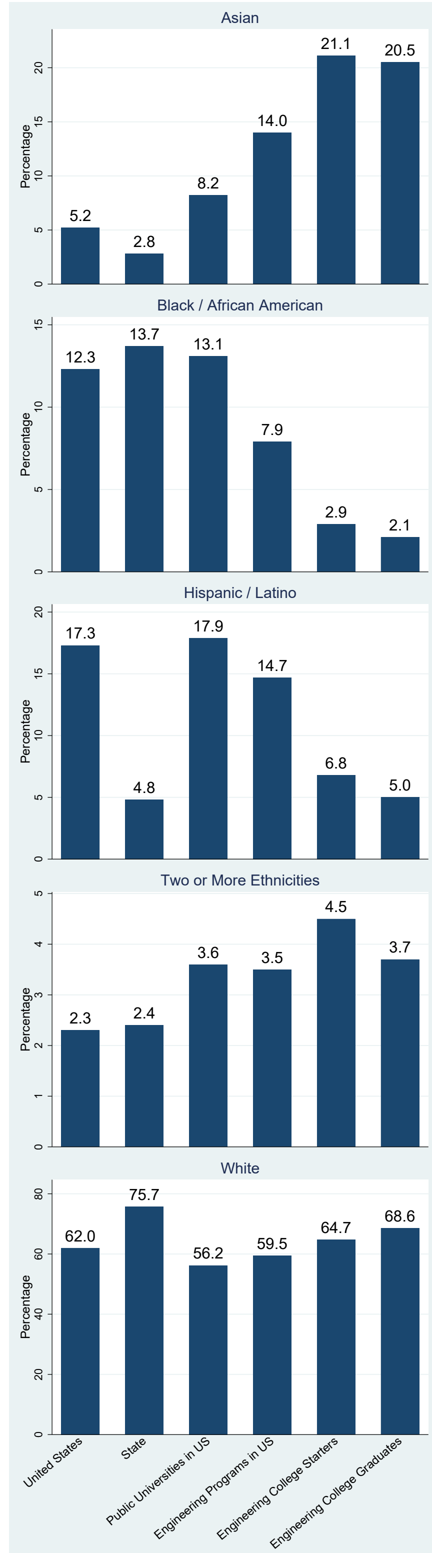


Figure 8.3: Percentage of populations by ethnicity [181, 182].

gories to be members of the working class, the socioeconomically-oppressed majority. The median annual household income in the United States was $67,871 in 2016 for families of two or more related members [181], but two-thirds of the students in our study were from households earning at least $100,000 per year. As shown in Figure 8.4, students from households making less than $50,000 per year, while comprising over a third of the national and state populations, made up a mere 13.1% of the engineering college's starters. (Note that, in Figure 8.4, the annual household income levels of $150,000 - $199,999 and $200,000 and above have been combined due to a lack of separation in the data from the NPSAS.) Compared to distributions at either the state or national level, this distribution was very statistically significant with $p < 0.001$. This is consistent with previous findings that socioeconomically disadvantaged students are underrepresented in engineering education [177, 178].

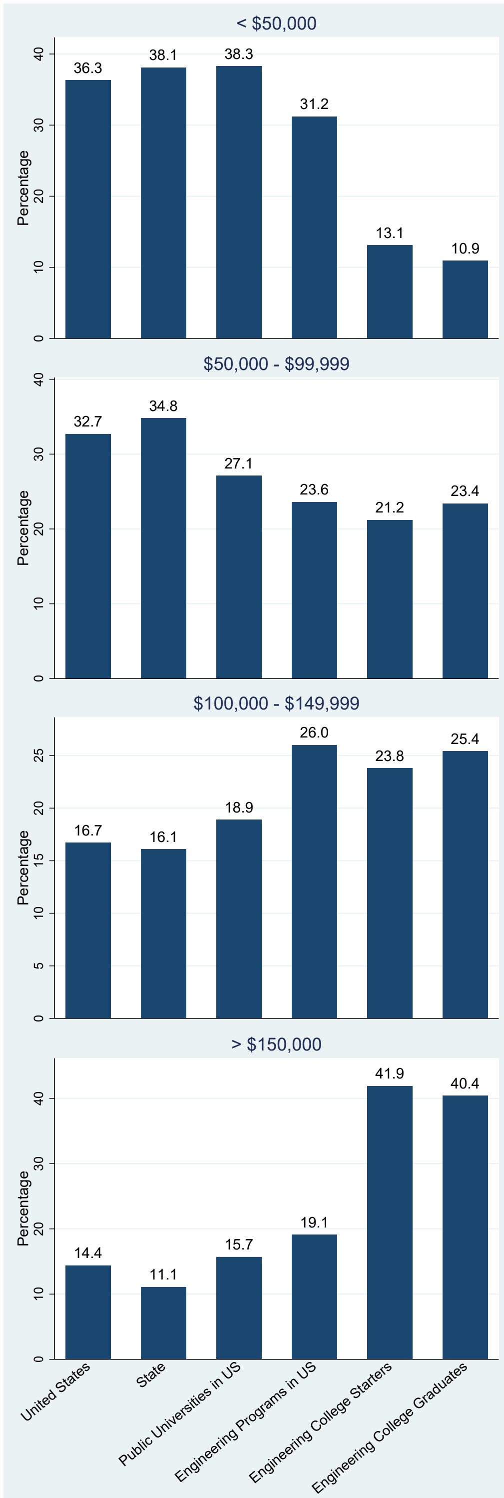


Figure 8.4: Percentage of populations by annual household income [181, 182].

The findings show that, while Black / African American students, Hispanic

/ Latino students, and working class students were all largely underrepresented groups, they also largely overlapped, as these two ethnicity subgroups contain significantly more working class students than other ethnic groups (see Figure 8.5). Conversely, the overrepresented groups of white students and ruling class students also share significant overlap. This is consistent with findings from the U.S. Census (shown in Figure 8.1) [181]. Thus, we begin to see the significance of the interaction between ethnicity and income level in our data, which are correlated with a statistical significance of $p < 0.001$.

8.4.2 Graduation Rates

Success or failure to earn a Bachelor's degree in engineering is a dependent variable in our analyses. We only considered students who entered the college between Fall 2011 and Fall 2013 in order to give them ample time to graduate; since the data is as

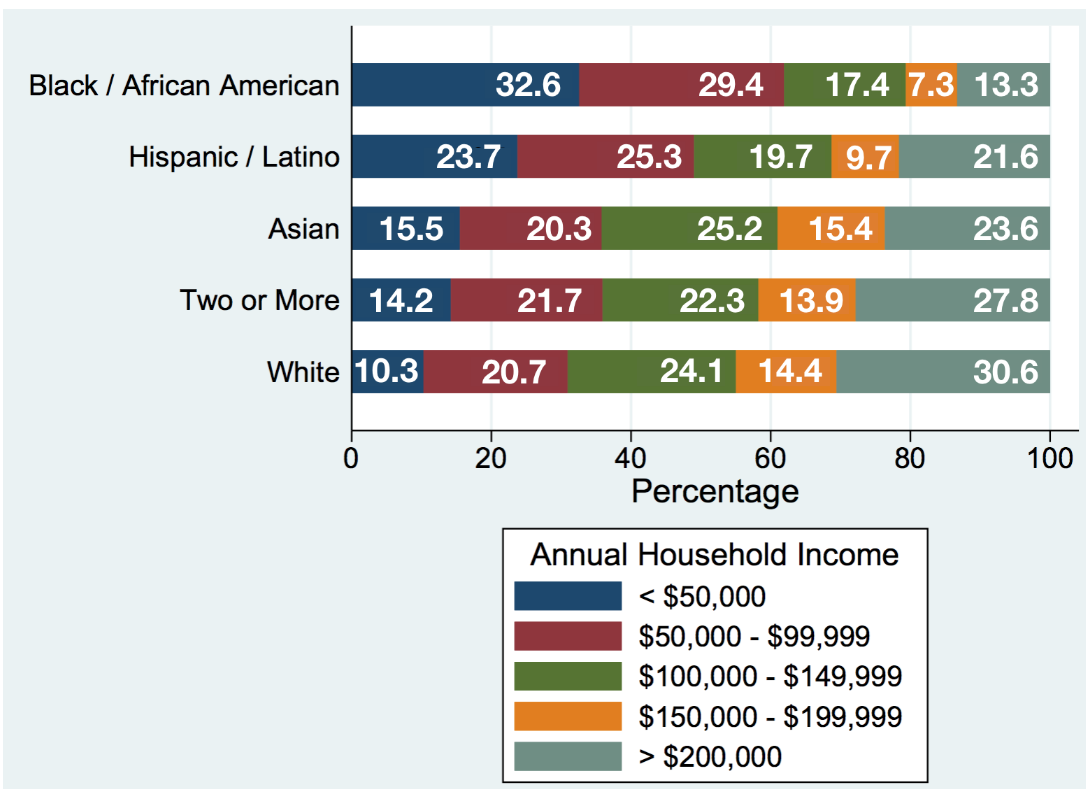


Figure 8.5: Distribution of annual household income by ethnicity.

of November 2019, the Fall 2013 cohort had had nearly six years to graduate, and the Fall 2011 cohort had had nearly eight. 2,930 of the students had either graduated or left the university and were considered for this analysis. Twenty-four students were still enrolled in the engineering college at the time the data was taken and are omitted from the analysis, but they account for less than one percent of the population. The frequency counts of gender, ethnicity, and annual household income are shown in Table 8.2.

Because the nature of the variable is dichotomous, I performed a logistic regression by converting each subgroup into an indicator variable. Thus, the regression fits the coefficients of nine indicator variables (one gender, four ethnicities, and four income ranges) to find the deviation of their likelihood of graduation from that of the intersectional base subgroup of white men coming from households with incomes at or above $200,000 per year. This subgroup was selected on the basis of liberative frameworks' theory of privilege for these particular subgroups.

The results of the logistic regression are shown in Figure 8.6. Gender was not found to be statistically significant in the model of graduation rate, consistent with many findings in the literature [126, 163, 167–169, 175] but contrary to others [172, 173]. Ethnicity and income were both statistically significant, however.

The model shows that Black / African American and Hispanic / Latino students, who, as we showed in Figure 8.5, are on average less wealthy than other ethnicities,

Table 8.2: Frequency counts of gender, ethnicity, and annual household income level for graduation rate analyses.

Annual Household	Asian		B / AA		H / L		Two or More		White	
Income	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
< $50,000	70	17	17	3	31	6	7	4	143	45
$50,000 - $99,999	88	42	15	3	34	10	17	11	373	116
$100,000 - $149,999	113	46	13	2	28	7	20	8	379	120
$150,000 - $199,999	66	34	4	3	11	3	13	2	202	80
> $200,000	77	25	7	2	27	9	23	8	383	163

Logistic regression	Number of obs	=	2,930
	LR chi2(9)	=	45.87
	Prob > chi2	=	0.0000
Log likelihood = -1168.6775	Pseudo R2	=	0.0192

Graduation Rate	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
Women	-.1464764	.1201964	-1.22	0.223	-.3820571	.0891043
Asian	.3455352	.1514227	2.28	0.022	.0487521	.6423183
Black / African American	-.5927976	.2905984	-2.04	0.041	-1.16236	-.0232353
Hispanic / Latino	-.5670363	.1966409	-2.88	0.004	-.9524455	-.1816272
Two or More Ethnicities	-.2216394	.261067	-0.85	0.396	-.7333213	.2900424
> $50,000	-.6514954	.1807176	-3.61	0.000	-1.005695	-.2972954
$50,000 - $99,999	-.433352	.1543297	-2.81	0.005	-.7358326	-.1308715
$100,000 - $149,999	-.1841062	.1597588	-1.15	0.249	-.4972277	.1290154
$150,000 - $199,999	.1223797	.2007409	0.61	0.542	-.2710652	.5158246
cons	2.085974	.1255455	16.62	0.000	1.839909	2.332039

Figure 8.6: Logistic regression of graduation rate (Base: white man with an annual household income above $200,000).

were also less likely to graduate. Our data of graduation rates subjugated by ethnic group are shown in Figure 8.7. These findings are consistent with those of other studies of persistence and graduation rates [127, 169, 174, 176]. As can be seen in Figure 8.3, white students were the only ethnic subgroup that increased in representation between matriculation and graduation in our data. The coefficients of the model, given in terms of log odds, can be used to calculate the odds of graduation for each indicator variable in comparison to the base. For example, the odds of graduation are 1.8 times better for the base student than for a Black / African American student with $p = 0.041$. Likewise, the odds of graduation for the base student are 1.75 times better than for a Hispanic / Latino student, with $p = 0.004$.

Income, however, was even more significant than ethnicity in this model. The single largest predictor of failure to graduate was an annual household income of less than $50,000, as the base student's odds of graduating were 2.0 times better than those of the low income student with $p < 0.001$. (As we saw in Figure 8.3, only 10.9%

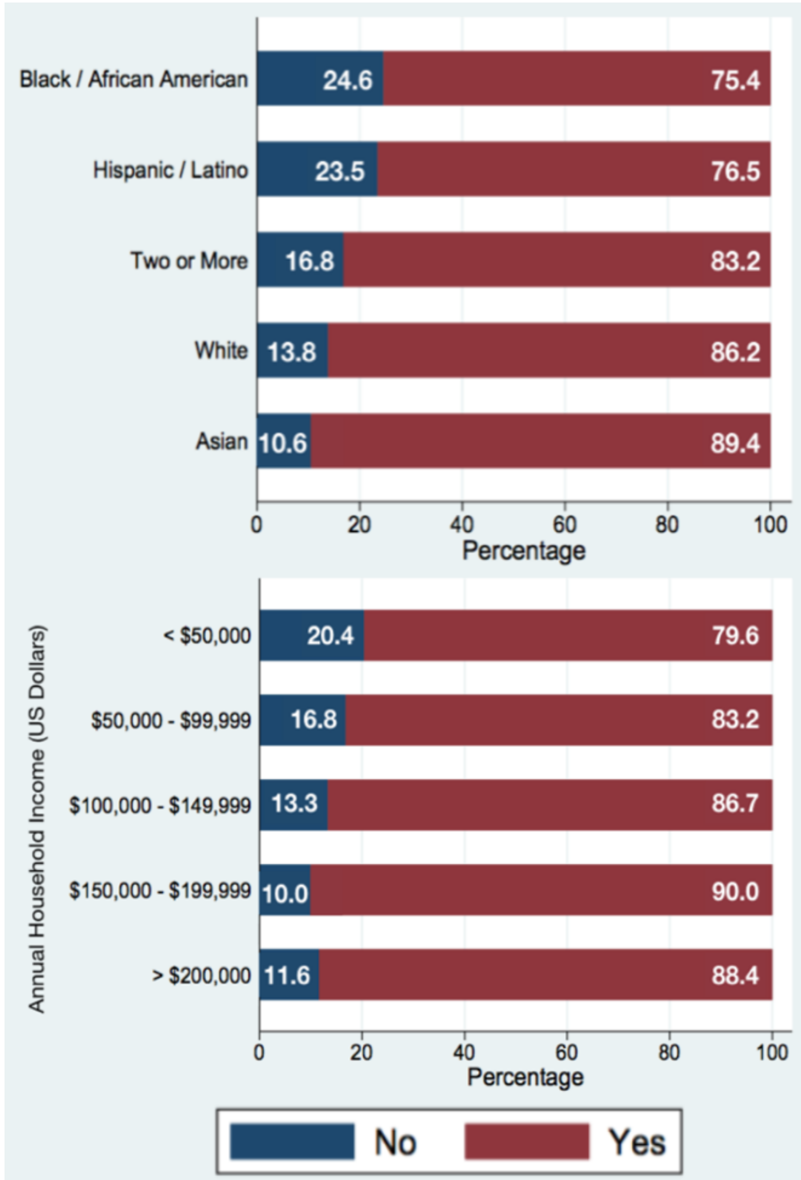


Figure 8.7: Graduation rate by ethnicity and annual income level.

of graduates were from households with annual incomes of less than \$50,000.) The base student's odds were also 1.5 times those of students from households of incomes between \$50,000 and \$99,999 with $p = 0.005$. Our data showed that increasing annual household income increased likelihood of graduation up to the \$150,000 - \$199,999 income level, after which point it stabilized. These results are consistent with previous findings that students from socioeconomically disadvantaged backgrounds exhibit lower graduation rates compared to their wealthier counterparts [104, 171, 177, 178]. The effect size of annual household income within our model, which is at or above that of ethnicity, demonstrate that ethnicity data alone are not sufficient to predict the likelihood of graduation for most students. Our data of graduation rates for various income level groups are also shown in Figure 8.7.

8.4.3 Time to Graduation

Time to graduation, the next dependent variable, is analyzed for the 2,277 cohort (non-transfer) students within the graduation rate analysis who successfully completed an engineering Bachelor's degree. The frequency counts of gender, ethnicity, and income level for these students are shown in Table 8.3. Time to graduation is a continuous variable that measures the time in years between the student's first enrollment in the engineering college and the student's graduation (including any semesters that they were not enrolled).

Analysis of Variance (ANOVA) tests are performed in order to determine the dependence of time to graduation on the independent variables. In addition to considering gender, ethnicity, and income individually, we also consider interactions between them in accordance with intersectionality theory.

A three-way Analysis of Variance showed no statistical significance on any independent variable within the model, including interactions, except ethnicity, which was significant with $p < 0.001$. Thus, we performed a one-way Analysis of Variance

Table 8.3: Frequency counts of gender, ethnicity, and annual household income level for time to graduation analyses.

Annual Household	Asian		B / AA		H / L		Two or More		White	
Income	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
< \$50,000	50	11	8	2	17	4	3	3	96	28
\$50,000 - \$99,999	71	28	12	2	24	6	15	8	263	80
\$100,000 - \$149,999	92	43	8	0	22	4	15	6	312	96
\$150,000 - \$199,999	56	26	3	3	6	2	11	0	174	69
> \$200,000	64	22	7	2	21	7	20	7	317	131

on ethnicity alone, yielding the model shown in Figure 8.8. This model shows that ethnicity accounts for 2.2% of the variation in students' time to graduation. From the plot of the adjusted predictions, we see that Black / African American students took a semester longer to graduate than other students on average, and that their results are the most sporadic (measured by standard error). White and Asian students, on the other hand, had the shortest average time to graduation, equal to about the standard eight semesters of study, as well as the most consistent results. These findings are consistent with those of Fenske, Porter, and Dubrock, who also found

Number of obs = 2,277 R-squared = 0.0235
Root MSE = .486029 Adj R-squared = 0.0218

Source	Partial SS	df	MS	F	Prob>F
Model	12.913315	4	3.2283288	13.67	0.0000
Ethnicity	12.913315	4	3.2283288	13.67	0.0000
Residual	536.70041	2,272	.23622377		
Total	549.61372	2,276	.2414823		

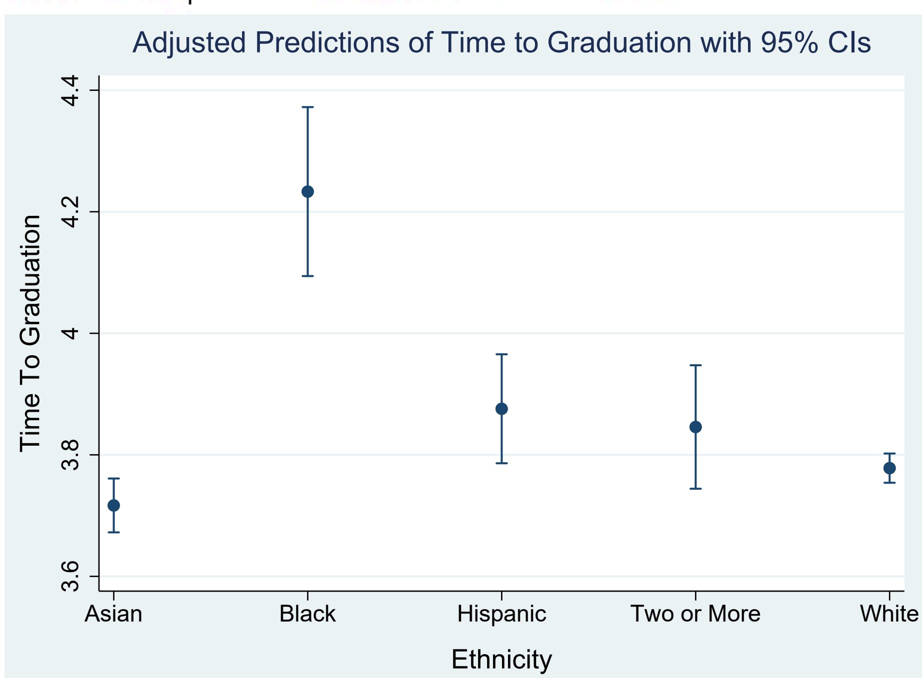


Figure 8.8: ANOVA model of time to graduation by ethnicity.

similar dependence on ethnicity in time to graduation for engineering undergraduates [171].

8.4.4 Grade Point Average

Lastly, I consider the dependent variable of GPA as a quantitative measure of student performance. Students' cumulative GPAs are taken from their fourth semester of study in order to strike a balance between early semesters, in which students take a limited number of engineering classes due to general education requirements, and later semesters, by which time many struggling students have withdrawn from the engineering college. By the fourth semester of study, the students in the engineering college have taken at least two semesters of major-specific coursework. Fourth-semester GPA is a continuous variable ranging in value from 0.842 to 4.198 (an A+ grade within the school of business at this institution was worth 4.3 towards a student's GPA during part of the time period from which this data was collected, so a few students who took business classes were able to achieve cumulative GPAs higher than 4.0).

ANOVA tests are performed to model the dependence of gender, ethnicity, income, and their interactions on fourth-semester GPA. 6,998 of the original 7,621 students included in the representation analyses received a cumulative GPA in their fourth semester after enrollment, meaning that they had not left the engineering college by that point or taken that semester off. Frequency counts of gender, ethnicity, and income for these students are shown in Table 8.4.

The results of a three-way Analysis of Variance, while significant with $p < 0.001$, do not show any significance of gender or of any interactions including gender. This is somewhat consistent with Lord et al.'s finding that women achieve equal or slightly higher GPAs than men but contrary to their result of Black / African American women achieving significantly higher GPAs than Black / African American men [126]. Due to the results of our three-way model, we instead perform a two-way Analysis of

Table 8.4: Frequency counts of gender, ethnicity, and annual household income level for grade point average analyses.

Annual Household	Asian		B / AA		H / L		Two or More		White	
Income	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
< $50,000	170	67	40	21	78	23	25	12	348	106
$50,000 - $99,999	213	89	41	18	88	26	40	28	722	198
$100,000 - $149,999	288	100	25	11	66	25	52	19	814	275
$150,000 - $199,999	161	69	10	6	31	15	33	12	489	176
> $200,000	271	84	19	7	76	27	63	22	999	400

Variance on ethnicity, income, and their interaction. The resulting model, which is shown in Figure 8.9, is dependent on all three components to a statistically significant degree and accounts for 4.8% of the variation in students' fourth-semester GPAs.

Ethnicity, which is significant with $p < 0.001$, had the largest effect on student GPA. Hispanic / Latino students were predicted to achieve GPAs that were 0.15 - 0.20 lower and Black / African American students were predicted to achieve GPAs that were 0.30 - 0.35 lower than those of students of the remaining ethnic subgroups. These findings are consistent with those of Lord, et al. [126]. Distressingly, the 95% confidence intervals for these three populations (Hispanic / Latino, Black / African American, and other ethnicities) do not even overlap in our model.

Income is also statistically significant in the model with $p < 0.001$. Our data had shown that lower income students had lower GPAs and performed more sporadically and higher income students had higher GPAs and performed more consistently (with consistency of performance measured by standard deviation). The behavior of the means and standard deviations in these results was completely monotonic. The 95% confidence intervals for the lowest income students do not overlap with those coming from households making more than $50,000 per year. The model predictions for the effect of income on GPA along with 95% confidence intervals are included in Figure 8.9.

Additionally, the ANOVA model found the interaction between ethnicity and income to be statistically significant with p = 0.013. In the interaction plot included in Figure 8.9, we observe that, for low income students, Hispanic / Latino and Black / African American students have significantly lower GPAs than students in the remaining ethnic subgroups. However, as income increases, Hispanic / Latino students are able to “catch up” to the remaining ethnic subgroups, but Black / African American students are not. This is an important finding, both in terms of intersectionality and the lack thereof, for Hispanic / Latino and Black / African American students, respectively. This finding may have important implications for further theory development, as access to financial resources is found not to be a means of overcoming racist social and educational structures for Black / African American students specifically.

8.5 Conclusions

This study looked at the program-related outcomes of engineering undergraduate students on the bases of gender, ethnicity, and annual household

Number of obs = 6,998 R-squared = 0.0510
Root MSE = .475555 Adj R-squared = 0.0477

Source	Partial SS	df	MS	F	Prob>F
Model	84.696731	24	3.5290305	15.60	0.0000
Ethnicity	29.290656	4	7.3226639	32.38	0.0000
Annual Household Income	12.99979	4	3.2499475	14.37	0.0000
Ethnicity # Annual Household Income	7.0053326	16	.43783329	1.94	0.0137
Residual	1576.9601	6,973	.22615232		
Total	1661.6569	6,997	.23748133		

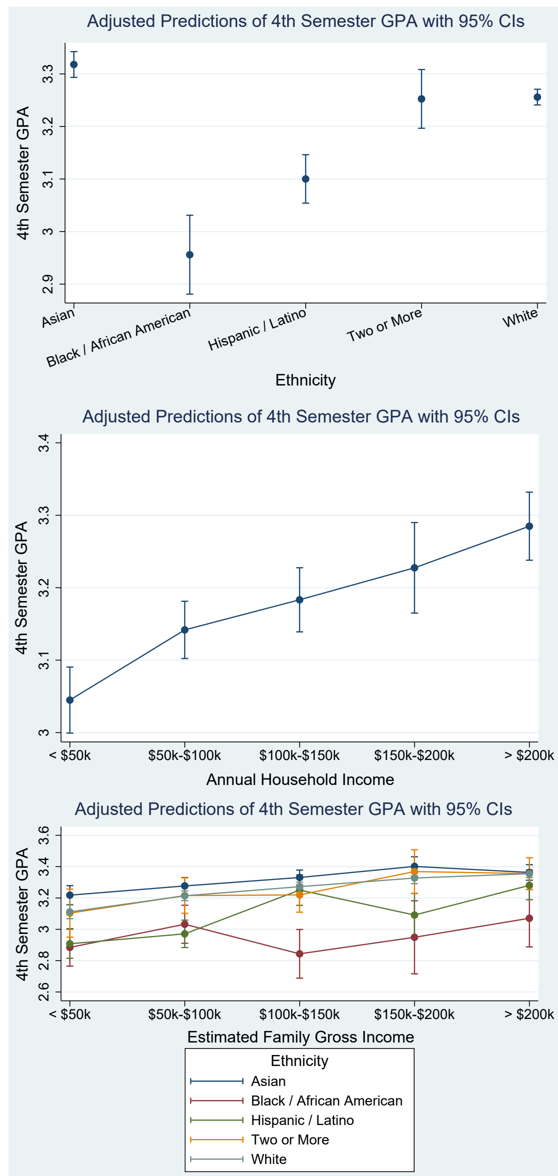


Figure 8.9: ANOVA model of fourth-semester GPA by ethnicity, income, and their interactions.

income at a large, research-oriented, highly selective public university. Consistent with the claims of liberative and critical theories, we found that students of marginalized identity groups, including women, people of color, and members of the working class, experience hindrances in their opportunities to access and succeed in engineering education. However, the ways in which the attributes of gender, ethnicity, and income interact with one another throughout the educational experience are varied and nuanced. The main findings of this study are summarized as follows:

- Women, Black / African American, Hispanic / Latino, and working class students are grossly underrepresented at this institution.
- Working class students have greater representation amongst Black / African American and Hispanic / Latino students.
- Students who are either Black / African American, Hispanic / Latino, or working class are less likely to graduate than those who are neither. Income is even more significant than ethnicity in affecting likelihood of graduation.
- Black / African American students take a semester longer to graduate than other students.
- Black / African American and Hispanic / Latino students have significantly lower GPAs than other students.
- Aggregated by ethnicity, students have GPAs that are approximately .06 higher for every $50,000 of annual household income.
- The GPAs of Hispanic / Latino students improve to the level of students who are not people of color for those of the ruling class. However, high levels of income do not improve the GPAs of Black / African American students.

These results demonstrate that, while we may be more aware of gender and ethnic minorities within our midst as engineering educators due to these groups' inescapable noticeability, working class students comprise an often-invisible minority group that is also fundamentally disadvantaged and in need of support. This is not to detract from the very real systematic marginalization experienced by students on the bases of gender and ethnicity that are documented in this study and others; rather, I hope to demonstrate how current social and educational structures are failing working class students in addition to women and ethnic and racial minorities. Many students of marginalized ethnicities will themselves receive the benefits from income-based educational support structures, since financial capital is disproportionately distributed across ethnic boundaries within our societies.

It is imperative that the results of this study be interpreted not as a failure of those of marginalized identities to thrive, but as a failure of those of privileged and powerful identities to enact conditions that allow marginalized populations to be successful. In future studies, we intend to better connect these quantitative results to the processes described in liberative and critical theories through qualitative study of marginalized engineering student experiences. As processes of oppression become better understood by engineering educators, further development and use of critical and liberative pedagogies [89, 109, 184–186] will be necessary in order to bring about structural change. Through a combination of awareness, advocacy, and solidarity, privileged and marginalized peoples can and must work together to overcome oppression in every societal space – including engineering academia.

CHAPTER IX

Critical Qualitative Analyses of Engineering Educational Experiences

9.1 Introduction

In Chapter VIII, some of the hindered academic circumstances facing working class students and students of color were identified, including underrepresentation, lower likelihood of graduation, increased time to graduation, and lower grade point average. The purpose of this study is to understand why and how these findings are occurring. Thus, the first research question for this study asks *what particular factors are causing marginalized undergraduate engineering students to experience underrepresentation and hindered academic outcomes*. It is necessary to identify these factors in order to address the sources of the problems at their roots, rather than enacting reactionary initiatives that label marginalized students themselves as the source of the problems (see Section 7.1).

The liberative theories we employ throughout this study are rooted in community-based, cooperative, and solidarity-focused methods [89, 109]. Thus, it is vital to the researchers that the participants not be objectified for the purposes of data collection, but rather have the opportunity to build collective understanding and empathy across their experiences through the data collection methods. Through collaboration, we hope they will be able to come to understand the breadth of structural systems of oppression and their effects. We also want them to develop confidence in their ability to demand and create constructive change as a group of organized individuals. Thus, our data collection and research methods are designed with these goals in mind, and a parallel research study asks *if these methods are successful in promoting the development of collaborative empowerment of the student participants*. This second research question is addressed using critical discourse analysis (CDA) methodology.

A team of graduate student and faculty researchers designed a series of events framed around the Theory of Liberation, titled the "Undergraduate Engineering Collaborative Growth Series" (UECGS). It should be noted that the co-investigator on the project, Joseph Valle, a Ph.D. Candidate in the University of Michigan Department of Materials Science and Engineering, was heavily involved in every step of the planning, data collection, and analysis. The UECGS is funded by an internal faculty grant from the engineering college focused on efforts to expand diversity, equity, and inclusion. The first event was designed to investigate the aforementioned research questions. In three follow-up events during the following semester, trainings will be conducted based on issues raised at the first event. The follow-up events and their resulting research are outside the scope of this study and thesis.

9.2 Methods

Through the process of this research, we strive for a diverse group of students from throughout the engineering college to have the opportunity to contribute to peer-reviewed research while also building collective understanding and empathy across their experiences. Through collaboration, we hope they will be able to come to understand the breadth of structural systems of oppression and their effects. The liberative theories we seek to employ in this study are rooted in community-based, cooperative, and solidarity-focused methods. Thus, our methods of data collection are designed to give students ownership over their own ideas and experiences.

The central activity of the first UECGS event was focus groups with collaborative, facilitated conversations on pre-determined topics related to the academic experience. In accordance with the application of critical and liberative frameworks, it was imperative that the event allow the student participants the opportunity to build power collectively rather than maximize the power and control of the researcher. For this reason, the faculty members on the research team did not attend the event, the event was hosted using a Zoom for Healthcare platform, which does not record video or audio [187], and the identities of participants are not known to the faculty members on the research team. These methods were employed in order to ensure that participants would not be at risk of retaliatory action for what they shared at the event. Because the event was not recorded, note-takers were employed to document the conversations within the focus groups, which serve as a major component of the qualitative data. The event was facilitated by myself and Valle, and focus group facilitators and note-takers were graduate students from the engineering college.

Facilitators, note-takers, and participants are all being financially compensated for their labors on this project, in recognition that student participation is labor which is frequently rendered invisible. Sharing experiences about harm, be it systematic, institutional, interpersonal, or internal, is an ask for emotional labor, so students must be compensated for that labor with liberative frameworks in mind. Participants in the UECGS are compensated $15 per hour for the duration of the events in the series, and facilitators and note-takers were paid $20 per hour for the events as well as for approximately two hours of professional training beforehand. Pay is distributed in the form of MasterCard Gift Cards.

9.2.1 Recruitment and Participant Selection

Institutional Review Board approval for the study, HUM00186437, was obtained from the institution at which the research was conducted. The first UECGS event was then advertised via email through our existing channels within the university, which included: 1) previous participants in a liberative activities event organized by a team of graduate student volunteers including myself and Valle, 2) identity-based engineering student groups on campus, 3) undergraduate engineering students in departments represented by members of the research team, facilitators, and note-takers, and 4) a daily newsletter sent out to the student body from the engineering college's Office of Student Affairs. Emails included a link to an electronic intake form. To communicate our desire to recruit marginalized students, it stated, "we are looking for participants with at minimum one of the following identities: women or non-binary, people of color, family background less than approx. $100,000 per year, LGBTQ+, or other marginalized identity." It then asked them to do the following:

- Provide their name, email, engineering department, and year (for which the choices were: Freshman, Sophomore, Junior, Senior, or 5th Year +)
- Indicate their gender identity, ethnicity, race, and sexual orientation via short-answer text
- Select the range into which their annual family income falls: less than $50,000, $50,000-$100,000, $100,000-$150,000, or above $150,000
- "Do you have any needs of the space such that you can feel safe engaging with this material? (This can include needs regarding other people's attendance impacting your safety. If such a need arises, we will figure out how to best meet your needs on a case by case basis.)"

- “Some of this material may evoke strong emotions for participants. If an exercise becomes difficult for you to handle, what are your needs from facilitators?”
- “Do you have any accessibility needs you would like us to know about?”
- “Is there anything else you would like the graduate student researchers to know?”

The research team’s goal was to secure about thirty participants in the UECGS, but ninety students filled out and submitted the intake form within only a few days of advertising. We feel that this is an important research result in and of itself. Given the goals of the UECGS as articulated to students via the intake form (“the researchers are seeking to better identify the barriers faced by marginalized undergraduate engineering students and provide trainings to equip students to work collaboratively towards change”), we conclude that there is immense desire within the student body for greater agency in enacting student-driven structural change within the engineering community. The self-reported identities of the applicants are shown in the left-side pie graphs in Figure 9.1. In this data, we have grouped the short-answer responses into the categories shown, and we followed up with the students individually in cases in which we were unsure.

It was decided by the research team and graduate student facilitators and note-takers that there should be approximately six participants in each of the six concurrent focus groups. We worried that larger focus groups might negatively impact student comfort and collaboration. Due to the need to select individual students to participate, Valle and I develop a framework to quantify marginalization, which is detailed in Table 9.1. Each applicant is assigned a total marginalization index by summing the point contributions from each of aspect of their identity shown in the table. The numerical values attributed to each identity are decided in light of the quantitative results in Chapter VIII. For example, the results indicate that Black/African American students and students from families making less than $50,000 a year are especially

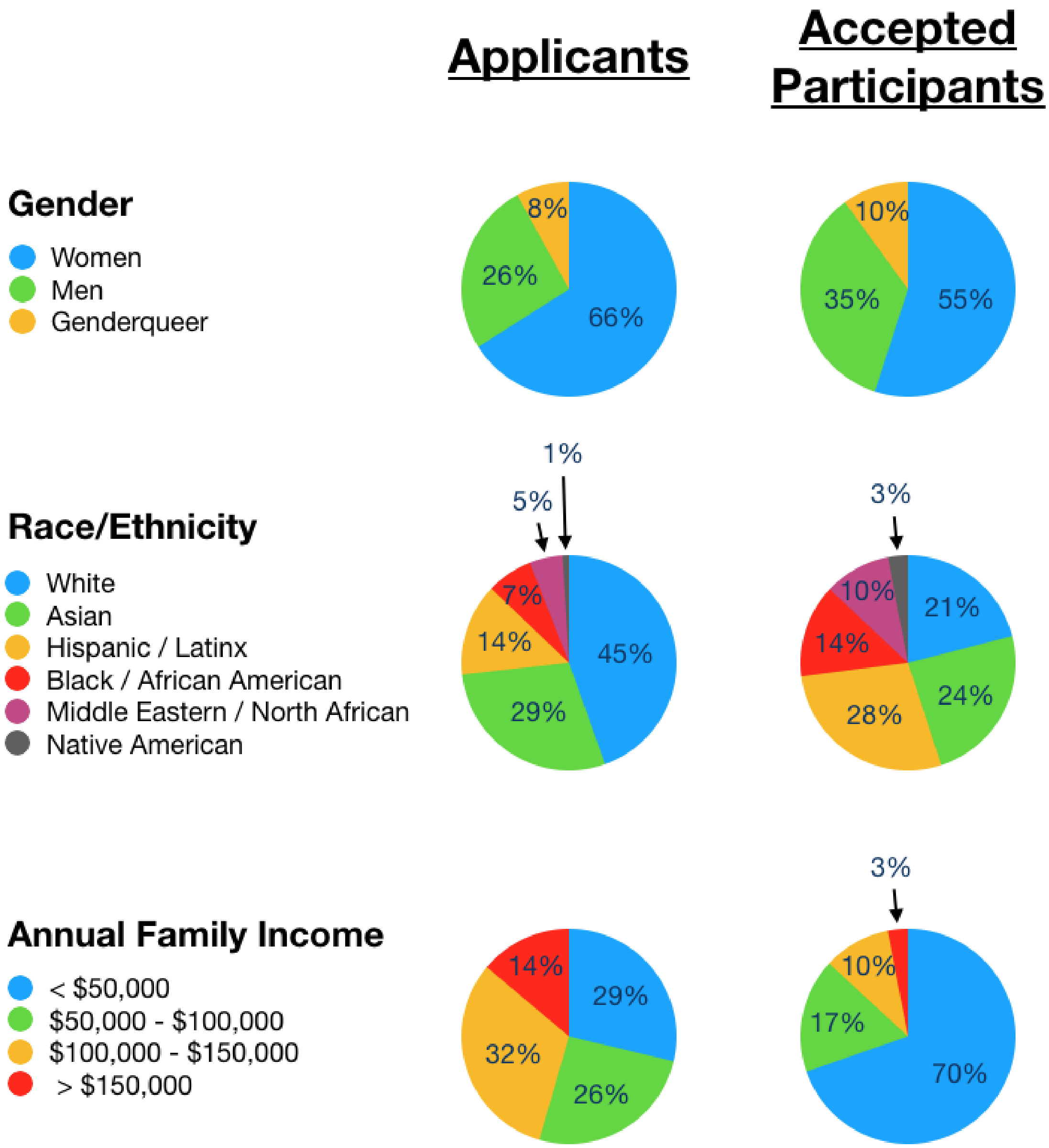


Figure 9.1: Self-reported identities of UECGS applicants and accepted participants.

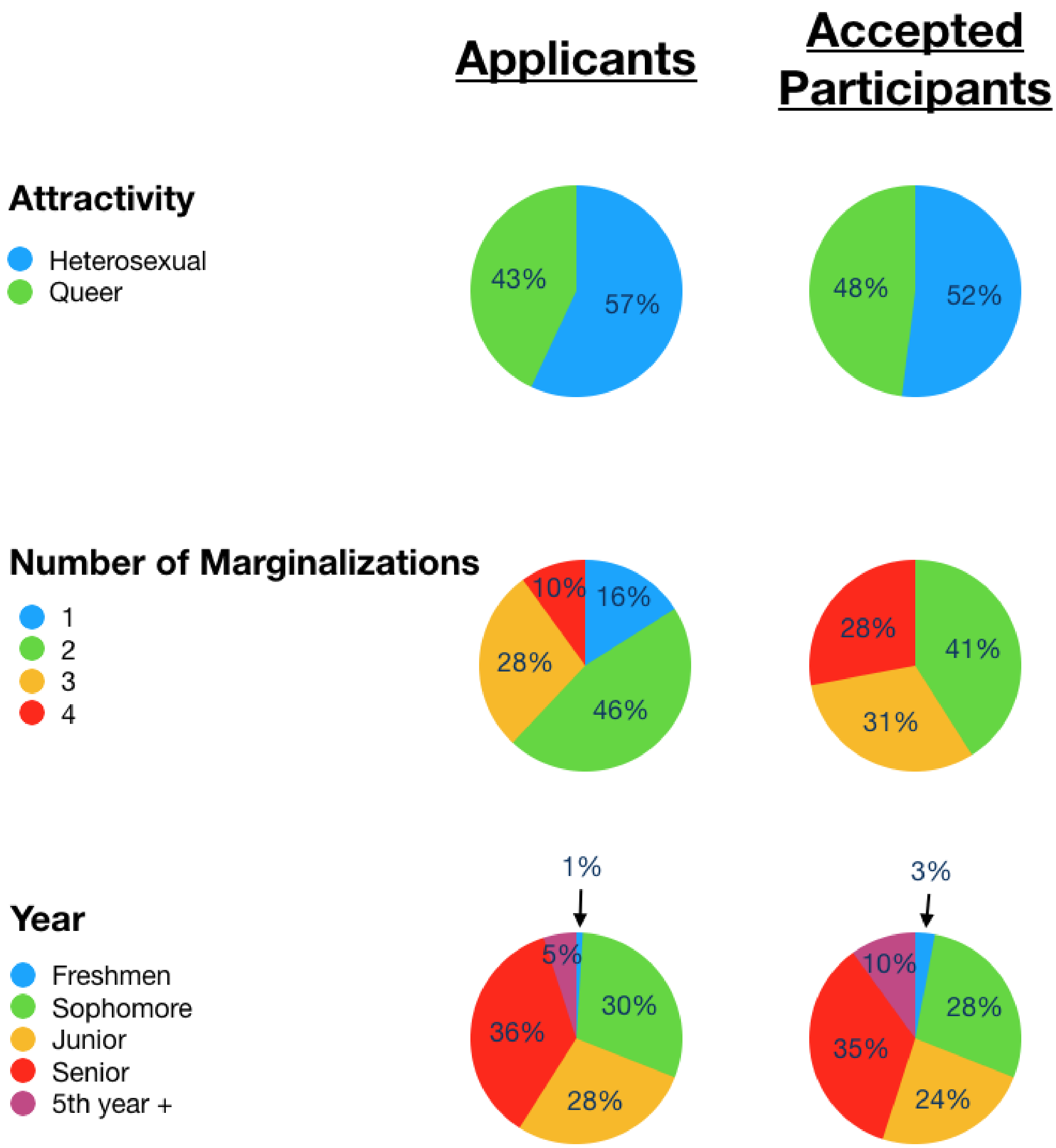


Table 9.1: Framework for a quantitative engineering student marginalization index (empty boxes had no points awarded).

Identity Aspect	1 Point	1.5 Points	2 Points	3 Points
Gender	Woman		Genderqueer	
Race/Ethnicity	Other non-white		Hispanic/Latinx	Black / AA or Native American
Annual Family Income		\$50,000 - \$100,000		Less than \$50,000
Attractivity	Queer			
Year	5th year +			
Ability	Disability			

hindered in academic outcomes, so these two groups are assigned the maximum of three points in the marginalization index. While women are extremely underrepresented in this engineering college (see Section 8.4.1), two-thirds of the applicants identify as women (see Figure 9.1), so women were not prioritized as highly by the marginalization index.

As shown in Table 9.1, one point is awarded to applicants who identify as having a disability, either physical or mental. However, this was not explicitly asked in the intake form. The researchers added one point to an individual's marginalization index if they self-identified as having a disability in their answers to the long-answer text questions in the intake form.

Each individual's race/ethnicity category (White, Asian, Native American, Black-/African American, Hispanic/Latinx, or Middle Eastern/North African) is determined from their answers to the short-answer "race" and "ethnicity" questions in the intake form. In the case of students whose answers were linked to multiple racial/ethnic categories, the one that is rated the highest number of points in the marginalization index is assigned.

As previously stated, ninety students submitted the UECGS intake form. The average marginalization index was computed to be 3.43 with a standard deviation of 1.65. We chose to admit students who had an index score greater than or equal to 4.00, which resulted in 38 admitted students. The demographics of the admitted students are shown in the pie charts on the right side of Figure 9.1.

In Figure 9.1, the last row of pie charts shows how many marginalized aspects of identity are attributed to a student out of the following: not white, not a man, not straight, and working class (defined as annual family income less than $100,000 per year). For example, a Black, working class, LGBTQ+ woman is defined to have four marginalized identities as shown in this pie chart. From these results, we conclude that our marginalization index was effective at prioritizing the participation of multiply marginalized students.

It is fully recognized by the researchers that a quantitative analysis of marginalization is inherently extremely problematic, as students' experiences with oppression cannot and should not be reduced to a single numerical value. However, this task is undertaken in order to prioritize the participation of students who are multiply marginalized. We also note that a similar marginalization index was utilized by Settles et al. in [188]. This marginalization index was not utilized in any of the data analysis later in this chapter.

The 38 admitted students were emailed a link to a second electronic form. The students were first asked to read and respond to the research participant consent materials. Students who selected "I give my consent," were then asked to provide a pseudonym to be used to refer to them in the research as well as their mailing address for delivery of their compensation. Finally, the students were re-directed to an external site, simpleassign.com [189], and asked to rank the six focus group topics in their order of preference. This free web-based service determined the best solution for matching people to their desired roles and topics [189]. The students were then provided with an online link to the first event of the UECGS, which was held virtually due to the COVID-19 pandemic. 31 students completed this consent and preparation process.

9.2.2 Facilitating and Note-Taking

Facilitators and note-takers were recruited from current graduate students in the engineering college known to myself and Valle. A diverse group of students with a variety of experiences in education research and/or advocacy work were asked to support the research in a paid role. 12 graduate students agreed to participate. Of the group of 14 graduate students, including myself and Valle, 10 identified as women or non-binary, 5 were non-white, 8 did not identify as straight, and 6 grew up in households with annual incomes of less than \$100,000 per year. Thus, it can be concluded that the body of facilitators and note-takers, while very diverse compared to the overall undergraduate student body (see Section 8.4.1), are not as diverse as the selected undergraduate participants (see Figure 9.1).

The graduate students first completed the required Human Subjects Research Protections course through the university's Office of Research Ethics and Compliance. They were then professionally trained during a ninety-minute session led by Vidhya Aravind, the Learning Director of We the People - Michigan, whom I and Valle employed due to her extensive experience both conducting and teaching effective facilitation. The training covered topics such as grounding, vulnerability, agency, honesty, multipartiality, and active listening. Also within the training, the graduate students worked collaboratively preparing potential facilitation questions for each of the six focus groups.

Finally, the graduate students ranked the roles of facilitator and note-taker and each of the focus group topics in their order of preference on simpleassign.com. Each facilitator/note-taker pair was notified of their assigned focus group topic in an email and encouraged to collaborate in any way they saw fit both in preparation for the event and within the focus groups themselves. Each pair was also provided with the answers submitted to the long-answer questions on the intake form from the students that would be participating in their focus group in order to prepare to accommodate any specific needs.

9.2.3 Data Collection

The first event of the UECGS took place in October 2020 and consisted of data collection for this qualitative research study. 29 admitted students came and participated. The event opened with an introduction of the research project and logistics. Methods of anonymity were highly emphasized and clearly explained. The following ground rules for discussions were briefly explained, which were adapted from a document originally authored by Vidhya Aravind [190]:

- Be and stay engaged
- Own your impact
- Strive toward vulnerability and openness
- Make sure everyone is heard
- Don't play devil's advocate
- Address ideas and not people
- Affirm and be generous in understanding
- Respect processing styles and honor silence
- Take care of yourself
- Remember your positionality

Zoom breakout rooms were then utilized to move the undergraduate and graduate students into the first focus groups. The Zoom host, Valle, moved the participants into breakout groups based on the optimization of the students' choice topics by simpleassign.com [189]. Six focus groups took place concurrently on the following topics:

- Belonging
- Recruitment and outreach
- Institutional diversity, equity, and inclusion
- Teaching and learning / the classroom environment

- Mentoring
- Conflict resolution

Each focus group lasted thirty minutes. The facilitator provided framing questions to students as needed to keep the flow of ideas coming and encouraged participants to build on each others' statements. They also contributed to the discussions, affirming participants' statements with their own thoughts and experiences, as modeled by Aravind during the training session. Note-takers also contributed occasionally to these conversations, further building community within the focus group. Facilitators and note-takers also encouraged the participants to utilize a Jamboard that was set up for each focus group beforehand [191], in which students were informed that they could write, draw or paste pictures, place sticky notes, or anything else they wanted.

After the first round of focus groups finished, everyone was given a ten-minute break, and then a second round of focus groups was conducted. After the second round was finished, all the participants and graduate students were brought back together to share and discuss the data they constructed and collected together as well as to recognize and discuss recurring themes that came up between the various topics. Finally, the event closed with a full-group visioning activity.

The entire group was invited to access a Google Doc [192]. The students were asked to build their collective vision of their desired future society to a bulleted list. They were also invited to add in sub-bullets below each item with questions that would need to be addressed and/or directions that we would need to move in as a community in order to create the vision. Two examples were provided on the document in order to establish the wide variety of scope that was welcomed; the first example was global in scope and the second was specific to the classroom environment. The visioning board as it appeared to the participants at the start of the activity is shown in Figure 9.2. While the student participants only had approximately five minutes to work on this activity, they filled over three pages with thoughts on their collective vision.

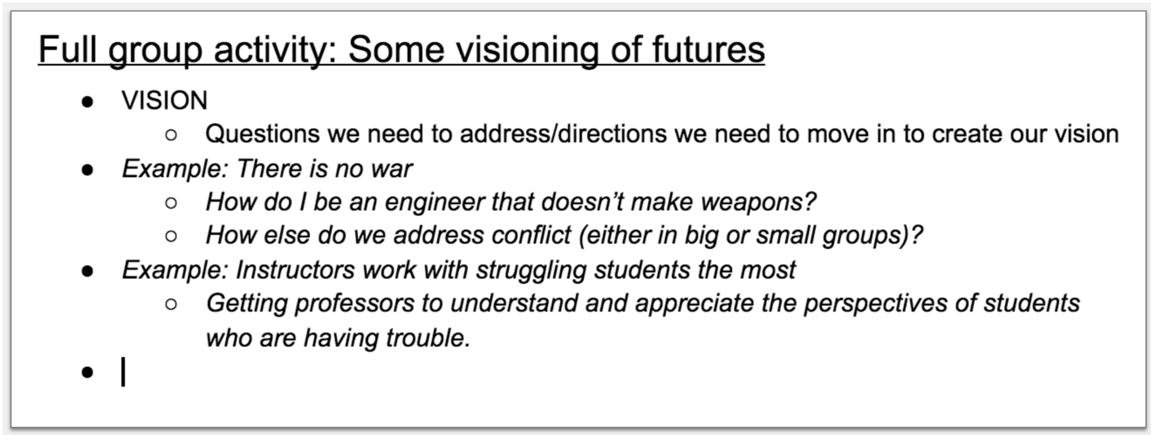


Figure 9.2: Visioning board with examples as it appeared to participants at the start of the closing activity.

Since the graduate student facilitators and note-takers were also eager to participate in the visioning activity, a separate section of the document was assigned for graduate student visioning, which, although outside the scope of this research, also produced interesting data and perspectives.

In summary, the complete qualitative data from the first UECGS event thus includes:

- Notes on the full-group discussions that took place before and after the focus groups
- Notes from the focus groups
- Jamboards produced by some of the focus groups
- Brief written reflections written by facilitators and note-takers after each focus group
- A bulleted list of ideas and obstacles generated by the participants as they envisioned their ideal engineering college community and world

9.2.4 Member Checking

Member checking was employed at various stages in the research, including live-checking during note-taking and four days of open review of the notes after the event. This member checking process was meant to ensure that participants' identifying information had been adequately anonymized and that the data collected was reflective of what the participants intended it to represent. Students did choose to participate in the member-checking process, clarifying their statements and deleting details that had the potential to identify them. Follow-up emails were sent to individual participants referring to specific sections and statements within the notes in order to ensure adequate anonymity. The participants responded diligently, and conversations and collaboration continued to check and shape the data for over a week after the event.

Once Valle, all the participants, and I were satisfied with the anonymization, participants' names were switched to the pseudonyms they had selected and all the data was copied and pasted into a new document with no file history. Only then were the faculty researchers allowed access to the data. Through this open and transparent process, the researchers are confident that the notes are accurate portrayals of participants' statements during the event and that risk to the individual participants is minimized.

9.2.5 Organizing for Change

In the following semester, three more events will take place to complete the UECGS. These events will offer skill-building trainings targeted toward the achievement of the students' collective vision. In this way, we hope to empower the students to build and shape their future communities. Valle is taking the lead on these, as they constitute a research project separately approved by the Institutional Review Board that will contribute to his own doctoral thesis.

9.3 Methodology

The data collection event described in Section 9.2.3 resulted in approximately 45 pages of multimodal data. Many different methodologies may be applied to this data in the future, as it is ripe for analysis. Two separate methodologies will be applied for this preliminary analysis: critical phenomenology and critical discourse analysis.

9.3.1 Critical Phenomenological Analysis Methodology

Phenomenology is a qualitative research methodology that highlights the commonalities of the experiences of research subjects [193, 194]. This is useful to our research process as we attempt to demonstrate the ways in which varied individual experiences of oppression are linked to overarching oppressive systems within our society. Phenomenological methodology aims to direct the focus of the research away from the researchers and onto the subjects and their experiences. The goal, then, is to reduce the data to a shared understanding of the common experiences, or phenomenons, of the subjects, from their collective point of view.

Critical phenomenology was first identified as a vital methodology for applications in scientific research by Herbert G. Reid in 1973 [195]. He wrote that "...possessive individualism, and mechanistic science - in the depth-historical perspectives of critical phenomenology - bequeathed to American liberal-capitalist society a tendency to a repressive language of domination" [195, p. 211]. In response, he calls for "the reestablishment of social science in a new, communicative interaction with the progressive forces of social and political praxis" [195, p. 243]. Thus, critical phenomenological research aims to connect structural inequity with the experiences of both individuals and collectives [196–198]. In engineering education research, this has previously been employed, for example, by Rodriguez et al. [199], who analyzed the experiences of five Latina undergraduate engineering students.

To conduct this analysis, Valle and I analyzed the entirety of the qualitative data, including the multimodal data within the Jamboards and the visioning activity responses, with respect to participants' experiences in engineering education. We each identified key themes and examples of them within the data and then compared and discussed our results until we achieved intercoder reliability. For this analysis, I will focus on the specific barriers we identified within the data. While there was variation in the ways in which individuals experienced and interacted with these barriers, they were frequent causes of hardship for the participants that they saw as affecting their academic experience. These barriers are listed and described in Section 9.4.1.

9.3.2 Critical Discourse Analysis Methodology

Discourse analysis, which is used to analyze texts, originally developed as a branch of linguistics but is now commonly applied in education, and sometimes engineering education, research [193]. Its critical branch was established largely through the pioneering work of Van Dijk and Fairclough (see, for example, [200]). Critical discourse analysis (CDA) has no rigid approach or methods, but rather encompasses a variety of processes through which analyses of power and oppression are conducted. For example, Berge et al. [201] applied this methodology to investigate the communication of gender and age norms in universities' websites on their engineering programs. For this study, the focus group data is analyzed using multiple methods within the umbrella of CDA, including analyses of genre, agency, and appraisal.

The specific subset of the data that is used for this project consists of notes from a focus group on the topic of diversity, equity, and inclusion (DEI) efforts within the engineering college. While the notes that were taken during focus groups vary significantly between transcripted discourse and overviews of general concepts discussed based on the style employed by the note-taker, this data was recorded by a note-taker whose work falls closer to the transcription end of this spectrum. It should be noted, however, that this work is not a word-for-word transcription of the spoken dialogue.

However, it is definitely sufficient for analysis at the clausal level.

Genre, agency, and attitude analyses, particular methodologies within the family of CDA, are employed to investigate the second research question: are the UECGS first event agenda and methods developed by the research team successful in promoting the development of collaborative empowerment of the student participants?

Genre Analysis

The analysis of genre is employed in accordance with the methodology outlined by Rose [202, 203]. The objective of genre analysis is to define the overall purpose of the discourse (informing, evaluation, story-telling, or procedure, see [203]) through specific language as well as the deconstruction of the text into stages, which outline the sections of the discourse through which the purpose is achieved, and phases, which further subjugate the stages into smaller sections that each contribute to the ways in which the discourse unfolds. Subdividing the text into stages and phases, and even further into individual clauses, aids the researchers in establishing what is achieved over the course of a complete text. One useful example of genre analysis applied to research in higher education is given in Askehave's discourse analysis of university advertising materials for prospective international students [204]. She demonstrates the corporatization of the higher educational environment through linguistic patterns; "we do not *teach* courses to *students*; we *sell* courses to our *clients*" (Emphasis in original, p. 725). Patterns also appear in the purpose and order of stages (or, as Askehave calls them, "moves") within a specific genre. The "move structure" she identifies in the advertising pamphlets provides the necessary basic information to prospective students in a predictable manner that also "sells" the university. While I only analyze discourse from one focus group within this study, my goal is to identify stages in such a way that other focus group discourses could also likely take the same structural form.

Agency Analysis

Agency analysis is begun using methods outlined by Halliday [205]. Each clause in the text is examined for evidence of agency, and instances of agentive "saying" and "doing" processes are noted. The actor (or agent) and the target (recipient) of the action are also identified. In some cases, the actors or targets were not defined by the speakers, and this was also noted. By definition, agency describes a form of individual power. In Listo's gender-based CDA of energy and poverty, she analyzes "constructions of women as victims" and "constructions of women as passive or objects" [206, p. 11]. She demonstrates that common claims in discourse that advances in energy technology are an empowerment tool for women are both unfounded and misogynistic. As such, it is imperative that we consider not only whether agency is demonstrated in each clause, but also the level of societal power afforded to the individuals involved.

This analysis thus also contains a coding of the amount of social and institutional power processed by the actors and targets. Power levels are defined both by the university structure as well as well as the perspective of the student participants. For example, "professors" and "administration" are always deemed "high" power and "students" labeled "low" power in the classification, but staff members are sometimes classified as "high" power, when referred to by the participants as decision-makers (e.g. "faculty and staff"), and sometimes as "low" power, when the participants clearly identified them as such (e.g. custodial staff). Graduate students were discussed in their roles as course instructors, specifically addressing the power they wielded within courses, so they are also classified as "high" power actors and targets. This coding scheme is an example of "versus coding," which is used to label two groups of social actors who are pitted against one another during social conflict [207]. Lastly, the individual clauses of discourse are also labeled with the time period during which the agentive action occurred: either during the focus groups themselves or prior to the start of the data collection event. This step is taken due to the desire to analyze if and how the participants build agency in the form of collective empowerment over the course of the focus groups.

Attitude Analysis

Attitude, a mode of appraisal, is also coded within the discourse. Appraisal is a discourse semantic system of systemic functional linguistics [208, 209], which is itself an overarching linguistic theory developed by Michael Halliday [205, 208]. The attitude framework is concerned with human feelings and responses [209]. Emotional responses are coded as "affect," perceptions of people and their actions as "judgements," and perspectives on situations as "appreciation." Each of these three responses are also coded as having positive or negative connotations within the discourse. This method of analysis is applied very similarly to that in Zhu and Wang's recent study of attitude within American president Donald Trump and Chinese foreign minister Wang Yi's speeches to the 72nd United Nations General Assembly [210]. That is, the attitude framework is applied at the descriptive, or textual analysis, level, and the results are examined quantitatively in addition to qualitatively. The quantitative results of different sections of the data can then be compared in a way that also takes versus coding into account. For example, Zhu and Wang compared the frequency of instances of affect, judgement and appreciation between Trump's and Wang Yi's remarks. Similarly, I compare the agentive statements with high- and low-power actors and targets identified within the focus group discourse based on the positivity or negativity of their attitudes. The analysis of attitude thus enables an organized dissection of the discourse that is, as the name suggests, both systemic and functional, and also helps decipher meanings from within interpersonal discourse.

9.4 Results and Discussion

The results of the phenomenological and discourse analyses are presented in Sections 9.4.1 and 9.4.2, respectively. Then, in Section 9.4.3, these results are considered together along with the structure of the data collection event to analyze the effectiveness of the event in relation to the theoretical frameworks and goals.

9.4.1 Critical Phenomenological Analysis Results

The following barriers are identified from the qualitative data as significant and frequent impediments to multiply marginalized students' successes within the engineering college.

Social Class

> "I've never really felt like I belonged [in the engineering college]. I came from a really bad school, test scores-wise. Coming from a small high school, mostly mixed, to [this university] was a big difference. [It was] hard to find people to relate to. [The engineering college] is really tough when you're with people who had a well-funded educational background and you are a person of color." - Lien

As the vast majority of the students in attendance were working class (see Figure 9.1), it was expected that money, or the lack thereof, would be a recurring topic of conversation. However, the specific circumstances of this public university's financial aid practices shape a particular situation that these students share as minority members of the university's working class community. Perhaps surprisingly, students loans were not addressed once. Rather, the students described their shared motivation for attending this university in particular to pursue their undergraduate education: its substantial financial aid packages. While the students frequently commented on the absurdity of tuition levels, there was a clear consensus that the financial aid packages offered were the "ultimate hammer," as one student put it, that led to their choice to come here. Thus, the biggest problem for working class students at this institution is not their ability to afford attendance, but rather the ways that their backgrounds affect them as members of the engineering community.

The students described, as Lien did, the connection between working class family backgrounds and working class educational backgrounds. Taylor shared,

> "I'm from a city on the Mexican border. My high school had very poor teaching. To come to [this university] and go to class with people who went to private [and other] great schools, [it] was very hard to catch up."

This was a frequently shared sentiment. The students noted that the "great schools" their white and affluent classmates attended offered many opportunities to prepare for higher education in STEM that they were never afforded. Their initial hopes to receive academic support from the university were not realized. Lien continued,

> "Not coming from a good high school, I assumed [the engineering college] thought I was smart and they would give me the resources to support me at [the university]. When I got here, they didn't give me what I needed. They just gave me generic help. I wanted more personal assistance for my educational background, to take summer classes, etc. I feel like the resources that [the engineering college] has aren't tailored to my needs and demands."

Despite the substantial financial aid packages, some students did report the need to hold down jobs while enrolled. Kiko, a woman whose chronic illness and multiple surgeries have also impacted her academics, describes the scheduling difficulties that arise from coordinating work and school. She stressed the importance of faculty posting class notes online and being flexible with office hours in order to accommodate students with jobs. However, students reported that professors attributed their lack of time to laziness rather than employment. Students also recognized the inherent injustice that some students are forced to have jobs during college in order to survive. From the final visioning activity, one point reads, “Students with financial burdens are given other opportunities at school that will allow them to keep up with the pace of students who don’t hold jobs down while attending college,” while another corners the root cause by simply stating, “Money shouldn’t impact education.”

Mental Health

> “Professors assume everyone has good mental health and are neurotypical, they aren’t understanding of diversion from their view. The pace of professors in class is un-inclusive, they move faster than I can for assignments and topics in courses. Professors try to teach following rules and being exact, very structured around their personal deadlines ([in a] workplace analogy: not meeting your bosses deadlines makes you a bad engineer). They look at you and see someone else.” - Dax

Poor mental health was a universally understood phenomenon that arose in the conversations of nearly every focus group. The focus was not strongly on specific diagnosed illnesses, but rather on the (overwhelmingly negative) state of the students’ mental health in general. Workload was identified as a major contributor to poor mental health, but, perhaps more importantly, the students identified a toxic attitude within the engineering community with respect to workload. As a student shared on the visioning board, they wished for a future in which “[they] don’t feel like [they are] not doing enough if [they are] not extremely stressed out all the time.” This points to an existing environment in which students have come to identify poor mental health as a signifier of good work ethic and react to *not* experiencing mental health issues with guilt.

There was a shared understanding amongst the students that the actions of many professors were exacerbating issues surrounding mental health. Professors are either unable or unwilling to accommodate mental health issues and don't understand the ways that their rigid teaching methods are directly contributing to the problem. As Melina explained,

> "I've had classes where the consensus is there's no respect for our wellbeing or the fact that we have other classes. They're not a disrespectful person in general but the way they act towards you is really frustrating. This has been a recurring theme in certain college classes and you'd think they'd be aware."

The issue with mental health seems to function as a vicious cycle: students experience deteriorating mental health, which negatively impacts their academic performance; students do not receive any empathy from professors regarding their mental health, which results in further mental turmoil; this additional anguish results in further worsening of academic performance. In response, students asked that professors' individual agency be bypassed by new university policies requiring flexibility in coursework - importantly, without requiring students to share details about their mental health status.

The university at which this study is performed has an internal counseling and mental health services center, but its primary office is located on a separate campus several miles from the engineering college. While there were also some concerns about the effectiveness of the services provided ("A friend of mine went to [the mental health services center] after having suicidal thoughts. He said [they] didn't do much addressing the issues and tried to push the blame around."), the months-long waitlists to receive service and lack of knowledge about the option to meet with the center staff on the engineering campus are unassailable obstacles to seeking help through the center. Students also connected their perceived lack of resources back to their marginalized identities. A note-taker commented in their reflection that students frequently connected the lack of mental health services and the lack of resources to support, for example, racial minorities and first generation students to a greater problem of poor advertising of all available support resources. One student spoke about their recent experiences with the college's centralized student support center, "[the center] has been very helpful but it shouldn't have taken this long to learn about [it]."

The Minority Tax

> "Professors generally have good intent but haven't really had non-binary students before so I get lots of questions that I don't need to be asked or even may be harmful. You know, you could do a Google search for that rather than putting me on the spot. I know they're coming from a genuine place, but that's not really an experience I've had outside the [engineering college]." - Moss

The students fully identified and frequently discussed that their multiply marginalized identities result in additional labors that are not performed by majority-identity students or by those with power within the university. Moss identified demands for this labor coming from not only professors in their department but also from the rest of the student body. In some cases, intentions to increase inclusivity only caused further harm. When another student brought up that graduate student teaching assistants are better than professors at demonstrating inclusivity and gave the example of graduate teaching assistants commonly asking students to provide their pronouns on the first day of class, Moss brought up that they dislike being forced to quickly decide whether or not to come out as non-binary in the classroom space; "every time I introduce myself with they/them pronouns, someone comes to me after and says something stupid." They suggest that "there's a better way ... to [ascertain pronouns] other than putting students on the spot." This begs the question: who comes up with these "better ways" and communicates them to the course instructors? Who comes up with ways to improve DEI in general?

This same question was posed in a focus group about institutional DEI efforts. Alex, a working class woman in a department with particularly low representation of women, immediately identified the answer as an example of the minority tax. She explained it as a matter of motivation: underrepresented students are most affected by problems with DEI and thus are motivated to create change, whereas majority students "don't have motivation to break down barriers for others." She described the efforts that she and her friends made to bring their ideas for improving DEI to their departments. She has not seen their ideas implemented; "[we] have the high-up discussions and the on-the-ground discussions but [they are] not connected." Stephen proposed that each department should create staff positions to serve the purpose of making this connection, a person "whose whole job is to talk to the students, get ideas, and talk to [the administration], so a connecting middle [person]." These positions would certainly alleviate much of the additional labor that is currently falling on minority students.

Many other students also discussed in their focus groups the work they and their peers continue to perform within the college in attempts to improve the environment. Karen, a Latinx working class woman, currently serves on the executive board for an organization in her department, working on DEI initiatives and community outreach events. When she made the point that the administration doesn't get involved in the labor she and her organization are performing, and even described a "wall" through which they effectively obstruct the group's efforts, Ramsey, a Latinx working class man, built on her statement to highlight their hypocrisy: "and then they blame students who do all of this work, if they do bad on one exam, then they shouldn't be doing this work and should be focusing on school." From the students' perspective, there is simply no way to win: either they continue their work to improve their conditions despite heavy discouragement from the university or they abandon their efforts and try to tolerate a hostile and inequitable environment.

Tokenism

"I feel like a diversity statistic." - Anonymous (via Jamboard)

Throughout the course of the event, the students developed a common understanding of their role as a minority token within the community of the engineering college. This is perhaps not surprising, as all of the students who participated in the event were marginalized on multiple fronts (see Section 9.2.1). The development of many individuals' experiences with tokenism stemmed from their experiences gaining admission to the university, engineering college, and/or their departments. Rather than celebrating their academic achievements reflected through their admission, the students frequently received pushback from their classmates, stating that their admission was a direct result of their marginalized identities. This was clearly a near-universal occurrence, as it was brought up by many different participants in several different focus groups. The emotional responses to these situations reflect worry, hurt, and the feeling of invalidation, all of which can be reasonably understood to negatively impact mental health as well as academic performance. (While these comments from peers reflect societal biases such as racism, classism, and sexism that transcend discussions of affirmative action policies, it may be worthwhile to note that affirmative action admission policies have not existed at the university in question since it lost a high-profile case in the United States Supreme Court approximately twenty years ago and such policies were declared unconstitutional [citation redacted for anonymity].)

In visioning their ideal future community, the students found themselves trapped in a paradox resulting from society's ostracization of their identities. Students railed against the tokenism they identified in their admission ("There isn't a need for colleges to target certain groups when recruiting just to meet a quota"; "No one assumes I got into a competitive college because of my minority status"; "Schools don't admit students of diverse backgrounds just to meet a quota, it's based on effort and hard-work") but also demanded fair and diverse representation not currently present in their engineering community. The students identified the challenge of overcoming this dilemma within the structure of their existing world; "How do we ensure that colleges don't become biased or segregated?" was posted repeatedly on the visioning board. Understandably, a consensus solution was not reached during the five-minute activity, but, in line with the tenants of critical race theory, it is clear but the students do not see incremental neoliberal solutions as a form of progress in societal efforts to address structural oppression. Rather, root causes of oppression must be addressed in order to create just and equitable communities [91, 92].

9.4.2 Critical Discourse Analysis Results

Now that some common barriers to student success have been identified and described, I turn instead to an analysis of how collaborative empowerment was developed through the use of focus group conversations. Several branches of critical discourse analysis are applied to the notes from one particular focus group, as discussed in Section 9.3.2. The notes, divided into clauses, are shown in Figure 9.3.

Genre Analysis

Genre identification is conducted at the level of the overall text. The genre of the focus group discourse is determined to be *evaluation*. In response to our phenomenological research question (what factors are causing marginalized undergraduate engineering students to experience underrepresentation and hindered academic outcomes?), the goal of the focus groups is to encourage students to evaluate their

Text	Phase	Stage
Facilitator: we've talked about things at a general level. What do you think of institutional DEI at [this institution]?	**Phase 1:** Facilitator Intro	**Stage 1: Defining the Problem**
Jake: I think it's actually pretty good, at eye level	**Phase 2:** Jake's Thoughts	
could be GSIs are the people we keep in contact with rather than professors		
Professor-wise, only one engineering professor I've had asked us our pronouns on the first day		
most of my humanities professors and GSIs asked us pronouns on the first day		
It's just my personal experience, but I think that engineering departments are less aware of DEI		
I think it may be because GSIs are generally younger, can actually empathize themselves with our undergrad experience		
Moss: I was talking a lot about this in my last group	**Phase 3:** Moss's Thoughts	
but generally I feel like the undergrad body has not done a very good job, in my personal experience		
when I came out as non-binary earlier this semester, the sheer number of people who didn't know what that was		
felt put on the spot and felt like I became this spokesperson for all gender non-conforming people		
made me really uncomfortable		
and that shouldn't happen for a school as big as [this] with other non-binary or trans people		
I can agree with GSIs being more understanding		
but even so as someone who doesn't fall into the male-female gender identities I personally really really do not like when they ask us to go around and share our pronouns		
not always comfortable coming out in every classroom		
every time I introduce myself with they/them pronouns, someone comes to me after and says something stupid		
I think there's a better way for professors to do this other than putting students on the spot		
Donatello: I wanted to stay the same thing	**Phase 4:** Donatello's Thoughts	
definitely gotten better but at the same time I think it's kinda BS, just there to make the school look good		
not necessarily faculty/teacher's fault, but the admin basically		
they kinda make it that way, and that's wrong, should go fully in		
It's gotten better, especially compared to my freshman year		
For instance, it's kinda like the education for faculty		
I feel like that should be a mandatory thing that people are aware of		
Facilitator: Yeah, that idea of a more surface/reactionary commitment came up in last group	**Phase 5:** Quick Follow-Ups	
Moss: It feels a bit trendy since it hasn't always been like this. Feels a bit fake.		

Figure 9.3: Notes on diversity, equity, and inclusion focus group partitioned into clauses, phases, and stages. Note that CoE stands for the institution's college of engineering and LSA is the college of literature, science, and the arts.

Alex: I agree with what everyone else has noted	**Phase 6:** Alex's Thoughts	**Stage 1: Defining the Problem (continued)**
that the trend that I've seen is that the newer people in education like GSIs in young professors seem more successful in DEI		
that's where I've noticed the most people being susceptible to change		
I've also noticed that people high up talk about DEI and are excited about it but hard to notice actual changes that come down to us that we see in person		
Also, my undergrad friends, we've come up with DEI [ideas?] and brought to departments but haven't seen implemented		
have the high up discussions and on the ground discussions but not connected		
Also, it's hard to be an inclusive and equitable environment when the student body isn't diverse in the first place		
That's the part that's talked about in my living community		
hard to make a diverse community when the pool isn't diverse to start with (because not recruited/accepted)		
That's something that extends beyond institution		
Facilitator: Are there changes that you'd like to see that might improve environment?	**Phase 1:** Facilitator Intro	**Stage 2: Offering Solutions**
Moss: I think freshmen coming in should have to go through DEI program	**Phase 2:** Moss's Thoughts	
Students who will be developing tech of the future		
it's really important to understand other's experiences and how hurtful it can be to have assumptions		
For instance, so many people told me how lucky I was because I got internships because I was a woman in the [very specialized engineering] field,		
and that was very hurtful because it was invalidating		
I was working twice as hard just to not get talked over		
There shouldn't just be a workshop, there should be a whole class		
Stephen: I feel like there should be a section of each department whose whole job is to talk to the students, get ideas, and talk to admin, so a connecting middle man. Like a staff position, facilitate discussion between the student body and admin about DEI	**Phase 3:** Stephen's Thoughts	
Alex: When I think of aero department community, usually focused only on students or student-faculty relationships. Should also include staff, for instance cleaning staff	**Phase 4:** Alex's Thoughts	
I wish that staff would be recognized as part of the community because they also inhabit the space		
I think that would make students more responsible and build interdependence between students and staff		
Donatello: I'm not sure how much internal communication happens or how much we can do about that	**Phase 5:** Donatello's Thoughts	
but maybe they just need to have more internal dialogues		

Obviously a lot of the faculty/staff aren't our age, aren't as young, approach these issues differently	**Phase 5:** Donatello's Thoughts (continued)	**Stage 2: Offering Solutions (continued)**
Making that communication a norm for them		
Alex: I made a super long list of ideas to improve DEI last year	**Phase 6:** Quick Follow-Up	
but I listed two or three that I thought of. If that'd be helpful to share, let me know		
Facilitator: one thing I'm curious about, when we say "institutional DEI efforts," which people are making those efforts?	**Phase 1:** The "Minority Tax"	**Stage 3: Digging Deeper**
Alex: This is something that's been explained to me, the minority tax		
people who are underrepresented are the ones who are motivated to do DEI work because they're most affected		
whereas majority groups aren't as motivated, don't have barriers so don't have motivation to break down barriers for others		
Facilitator: All of y'all are CoE students. Do y'all have impressions of CoE efforts vs department efforts?	**Phase 2:** CoE vs LSA	
Moss: When I talk to people in LSA, they're much more accepting		
It's an internal struggle every time I go to a new engineering class about whether I'll reveal my pronouns or my name, since it's different from the name I use on canvas		
Alex: I've noticed the same thing in my engineering classes		
I feel like they're less open to DEI, compared to LSA or other elective classes		
(**Facilitator** return to earlier convo about DEI seeming trendy)	**Phase 3:** Intent	
Alex: I think intent is necessary to increase DEI		
but it's not foolproof, even if you have good intent, you can still cause harm or not include someone		
Intent helps, but not 100% guarantee that good will come from it		
Moss: Like what Alex said earlier	**Phase 4:** Harm from Phase 1-3 Topics Combined	
hard to represent people who aren't included in the student body		
Professors generally have good intent but haven't really had non-binary students before		
so I get lots of questions that I don't need to be asked or even may be harmful		
You know, you could do a google search for that rather than putting me on the spot		
I know they're coming from a genuine place		
but that's not really an experience I've had outside the CoE		

perceptions of care and support, or the lack thereof, within the engineering college community. Elements of this discourse demonstrate that the focus groups were effective in this regard. Evaluative patterns were cued by instances of verbs such as "think," "feel," and "agree," as well as comparisons and statements on how things "should" or "should not" be.

In performing a genre analysis of this subset of the data, the complete text is divided into the three *stages* of the conversation: defining the problems, offering solutions, and digging deeper into the analysis. The first two stages consist of *phases* in which each person offered their perspective on the stage. In each of the first three phases of the third stage, Alex and Moss identified a key issue relevant to both previous stages. In the last phase of the third stage, Moss offered their testimony of the harm they experienced from the combination of the three key issues identified. Thus, the third stage of the conversation builds directly from the largely free-standing first and second stages, and the fourth phase of the third stage combines the largely free-standing first, second, and third phases, offering a single testimony that effectively addresses the issues raised in the entire conversation.The partitioning of the text into stages and phases is also shown in Figure 9.3.

This analysis begins to demonstrate the ability of the students to build collective agency, or empowerment, themselves. It is important to note that the facilitator did not dictate the conversation, but only provided loose scaffolding, such as the introductory questions in Phase 1 of Stages 1 and 2. The students built on each others' statements in affirmation and connection. The most telling example of this is Moss's testament of harm in the last phase of the discourse. Moss was not responding to any particular question posed by the facilitator, and their statement effectively summarized the topics of each of the previous three phases and applied them in a personal way, building on contributions from Alex and the other participants. They not only felt comfortable enough within the group to share their personal testament but also contributed greatly to the collective knowledge of the group. This newfound collective understanding is a vital step toward collective empowerment, as will be discussed in Section 9.4.3.

Agency Analysis

Next, agency analysis is performed at the clausal level. Of the 76 individual clauses within the text, 34 are found to be agentive, with similar proportions of "saying" and "doing." This makes sense in conjunction with the students' common complaint throughout the event that poor communication is a major source of environmental problems regarding DEI within the engineering college. Notably, several of the non-agentive statements specifically call out an actor and reprimand them for not taking agency, such as when Moss states that "the undergrad body has not done a very good job" of internalizing and acting on efforts to improve DEI within the college. Additionally, only 12 of the agentive clauses name both the actor and the target of the action. These well-defined agentive clauses are listed in Figure 9.4.

In examining the actor and target power levels and the time period of these 12 clauses, the pattern is quite telling. There are 6 cases of actors with high power levels performing agentive actions that target people with low power levels, and all 6 of these cases happened in the past. There are 2 cases with low-power actors and high-power targets, both of which happened in the past. Finally, there are 4 cases with actors and targets both with low power levels, and all 4 of these cases refer to actions that took place during the focus groups.

It is not surprising that there are no cases of high-power actors or targets that occurred during the focus groups, because the only high-power participants in the focus groups were the facilitator and the note-taker, who only contributed sparingly to the conversations. However, an important result here is the high ratio of high-actor/low-target agentive actions to those of low-actor/high-target (6:2). This demonstrates

Text	Speaker	Attitude Framework	Actor	Actor Power	Target	Target Power	Time
most of my humanities professors and GSIs asked us pronouns on the first day	Jake	+ judgement	humanities professors and GSIs	high	students	low	Past
Professor-wise, only one engineering professor I've had asked us our pronouns on the first day	Jake	- judgement	an engineering professor	high	students	low	Past
but even so as someone who doesn't fall into the male-female gender identities I personally really really do not like when they ask us to go around and share our pronouns	Moss	- judgement	GSIs	high	students	low	Past
I think there's a better way for professors to do this other than putting students on the spot	Moss	- judgement	professors	high	students	low	Past
so I get lots of questions that I don't need to be asked or even may be harmful	Moss	- judgement	professors	high	Moss	low	Past
You know, you could do a google search for that rather than putting me on the spot	Moss	- judgement	professors	high	Moss	low	Past
could be GSIs are the people we keep in contact with rather than professors	Jake		students	low	GSIs	high	Past
Also, my undergrad friends, we've come up with DEI [ideas?] and brought to departments but haven't seen implemented	Alex	- appreciation	Alex and her friends	low	department personnel	high	Past
I agree with what everyone else has noted	Alex		other members of focus group	low	the focus group	low	Focus Groups
I was talking a lot about this in my last group	Moss		Moss	low	previous focus group	low	Focus Groups
but I listed two or three that I thought of. If that'd be helpful to share, let me know	Alex		Alex	low	this focus group	low	Focus Groups
Like what Alex said earlier	Moss		Alex	low	this focus group	low	Focus Groups

Figure 9.4: Clauses from diversity, equity, and inclusion focus group in which agency occurs and actors and targets are identified.

how the participants described their past experiences with DEI in terms of actions that were done to them by people with institutional power, rather than by their own efforts to appeal for change. For example, Moss further describes their reaction to being put on the spot by their instructors:

> "As someone who doesn't fall into the male-female gender identities, I personally really, really do not like when <u>they ask us to go around and share our pronouns</u>. [I am] not always comfortable coming out in every classroom. Every time I introduce myself with they/them pronouns, someone comes to me after and says something stupid. I think there's a better way for professors to do this other than <u>putting students on the spot</u>."

The two agentive statements in which the actors are named (their professors) are underlined above. In one of the cases in which students did appeal to those in higher positions of power in a display of agency, Alex stated that she and her friends had brought their ideas for improving DEI forward in their departments, but noted that they had not seen any of them implemented. These examples also illustrate the significant impact of the actions of those with power, as opposed to the futility of the efforts of the students.

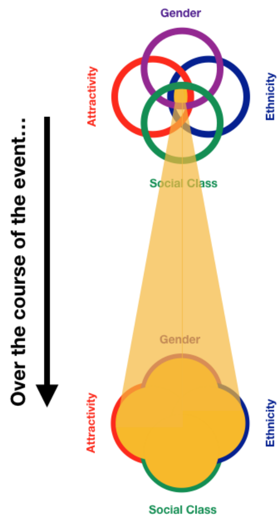
Attitude Analysis

Looking at the results of coding for attitude in the same twelve agentive clauses also shows an obvious pattern: five of the six high-actor/low-target clauses show negative judgement (see Figure 9.4). This is demonstrated in Moss's above statements. Additionally, one of the two low-actor/high-target clauses is coded as negative appreciation, as Alex clearly laments the failure of the engineering departments to enact her and her friends' suggestions. Thus, the students' interactions with powerful members of the engineering community in regards to DEI are overwhelmingly negative.

Finally, the lack of agentive statements describing actions by low-power actors onto low-power targets outside of the focus groups is a notable result. While the low-actor/low-target clauses referring to actions that occurred during the focus groups do not display attitude, all of the statements coded as low-actor/low-target involve constructive, consensus-building dialogue. The fact that no similar clauses are coded outside the focus groups suggests that the present work of students creating shared understanding through effective communication and collaboration does not occur frequently within the engineering college. However, the examples of collaboration in these clauses, such as Alex's offer to share her prior DEI work with the group, demonstrate the success of the focus group structure in providing a space that nurtures collective empowerment.

9.4.3 Intersectional to Liberative Foci

Considering the results of the phenomenological and discourse analyses together, we can examine how the structure of the data-gathering event progressively built collective empowerment amongst the participants. As shown schematically and in tabular form in Figure 9.5, the participants were selected individually by the merit of their intersectional identities. The focus groups, however, contributed to the development of a new community who shared common experiences such as the hindering effects of working class status, mental health issues, the minority tax, and tokenism. A supportive and affirmative but largely unstructured facilitation environment allowed the community to grow their collective understanding and combat individual isolation through the focus groups. This common understanding is built over the structure of the stages outlined in the genre analysis. This represents an intermediate step in the event's goal of adopting a fully liberative framework. This is achieved through the transformation of each participant's power source from individual agency to collective empowerment. The agency and attitude analyses with versus coding applied



Theory / Framework	Focus	Form of Power	Activity
Intersectionality	Particular Combination of Marginalized Identities	Individual Agency; Personal Influence	Selection of Participants
Intermediate Step			Focus Groups
Liberation	All Marginalized Identities	Collective Empowerment	Full-Group Visioning

Figure 9.5: Schematic and tabular demonstration of use of liberative frameworks to build collective power through research activity.

demonstrate the necessity and potential effectiveness of this transformation. The final visioning activity enacts the goals of collective liberation, bringing people of all marginalized identities together to build a future that frees humanity from marginalization and oppression. Thus, through their participation in this event, the students gradually transitioned from viewing the plight of their negative educational experiences from intersectional to liberative perspectives. This process is shown in Figure 9.5 using elements of the model developed in Section 7.1.

Future activities in the next three UECGS events will continue this effort to empower the group by providing trainings specific to the goals outlined in the visioning activity. Our research team hopes that these trainings will empower the group to shape and construct their future communities. Further analyses of the discourses within these skill-building processes could be used to confirm the continued development of collective empowerment. This would help us to demonstrate the effectiveness of our event's structure at bringing people of all marginalized identities together to build a future that frees humanity from marginalization and oppression.

9.5 Conclusions

"What has made any experiences within [the engineering college] feel positive or successful?" the facilitator asked during a focus group about mentoring. The response, wrote the note-taker, was "crickets." The note-taker prodded the group, "Does this mean... no positive experiences?" "Someone's ability to sympathize and be relatable," Leila finally responded.

Leila's answer targets the goal of the event itself. In bringing together students who are multiply marginalized - thus, likely accustomed to being the "other" to an endless degree within the engineering college - the goal is to produce collective empowerment through collaboration with other "others." In other words, students who have difficultly finding peers or mentors who are able to relate to them are able to find that relatability in others with the same problem. At the end of the event, several students stayed on the call and expressed their appreciation for the construction of the structural foundations of an engineering student community that did not exist prior to the event. The positive impacts of this can be seen in simple interactions that develop community as well as in changes in how students approach oppression within their lives; collective recognition and action against structurally oppressive systems is far more meaningful and effective than individual attempts. At the time of this study, we are living within a concrete example of this phenomenon through the Black Lives Matter movement, and the academic setting is not exempt from racial and other forms of injustice and oppression. The future UECGS events will continue to build this engineering student community and their collective power.

The Theory of Liberation speaks to the need to build solidarity in order to encourage the dismantling of structurally oppressive systems, and we need to begin this process with those in the engineering college who have the least amount of institutional power: the students. Only they have the ability to fully understand their own experiences, positionality, and needs. The best support that the engineering college can provide is not to dictate the terms of progress, but rather to empower students to shape their own communities.

In the same focus group, the facilitator later asked, "If [the engineering college] did try to create a mentorship program and reach out to you, how receptive would you be given your past experiences?" The note-taker wrote, "more crickets, saved by the bell / breakout room end." The results of this study show that the students most impacted by the current decision-making processes cannot and will not get the support that they need from those with institutional power - but that they can get that support from each other. Future work will continue to build on these findings as the community progresses in its collective empowerment.

CHAPTER X

Conclusions and Future Work on Engineering Educational Systems

JS is a non-white working class woman in her fifth year of study as an undergraduate in the engineering college. In one of the focus groups described in Chapter IX, she talked about an experience that made her acutely aware of her identity as a woman in engineering. JS has ADHD, and one of the three women professors she had taken a class with over the course of her undergraduate career made significant effort to aid her with effective learning strategies. JS greatly appreciated this effort and deeply admired the professor. However, she noticed that students acted very differently with this professor than they did with professors who were men. The woman professor "had to put her foot down," as JS explained it. In response, the students "either loved or hated her." JS witnessed students talking poorly about the professor online, and she felt badly and "didn't know what to do about it." Then, the professor received very poor mid-term evaluations from the students in the class. She chose to address the evaluations openly with the class. While discussing it, JS said that the professor "showed her humanity while also trying to remain professional." Referring to the entire situation, JS said, "It really sucks... I wouldn't want to be the professor."

I served as the facilitator for this focus group. I was taken aback by this final comment from JS. The note-taker also fixated on this statement; "are [students like

JS] now no longer interested in becoming faculty?" they wrote in their reflection.

JS's anecdote and conclusion illustrates an important symptom of structural oppression: chronic and cyclic underrepresentation. The absence of women in engineering is blatantly noticeable, but recruiting more women in Bachelor's degree programs will not spontaneously create more equitable conditions for those women, and it will not necessarily ensure their retention and success. The roots of structural inequity run deeply in the forms of sexism, racism, classism, homophobia, xenophobia, and other kinds of oppression in society. This part of the thesis addresses structural oppression within engineering educational systems using theoretical, quantitative, and qualitative research paradigms.

The theoretical research built on existing identity-based theories by situating them relative to one another in a model of their scopes. This model will aid engineering educators who are not familiar with these frameworks in applying them to future engineering education research. I then developed a theoretical model that highlights the profiteering purpose behind the perpetuation of cycles of Western military imperialism and demonstrates that engineers are capable of using their position within the system to dismantle this cycle. This serves as an example of applying Freirean critical theory to engineering systems. Theoretical work is not common in engineering education research spaces, and future research could continue to fill in the gaps in our sociological understandings of engineering and engineering educational systems. For example, future research into critical theory and engineering education could examine the roles of corporate structures such as those described in McLaren and Farahmandpur in engineering academia [95]. Additionally, as Riley has pointed out, better coordination is required between engineering education researchers and those in the fields of women's studies, ethnic studies, and the history of science and technology [109]. Theoretical developments incorporating interdisciplinary methodologies would also be valuable in engineering education research.

This part also applied critical and liberative theories to the quantitative study of undergraduate engineering student outcomes. This study examined the effects of gender, race/ethnicity, and social class on educational opportunity and performance at a highly-ranked American public university. I found that students of color and working class students experience lower rates of graduation, prolonged time to degree, and lower grade point averages than students who do not fall into either of these categories. These results are heavily influenced by the intersectionality of students of color and working class students, as the two groups largely overlap both in the United States population and within the engineering student body. However, the scope of this research is limited to a single selective public research institution, and it does not compare results from engineering with those from other fields. It also does not mathematically correct for differences in cost of living in individual students' hometowns. Future research could track the demographics and outcomes of undergraduate students at a variety of higher educational institutions, including less selective public universities, private colleges and universities, and community colleges. Additional analyses could compare outcomes on the bases of institutional demographic diversity, tuition rates and local costs of living, and programs of study.

To close this part of the thesis, a qualitative research study helped us to better understand the mechanisms through which the disappointing quantitative outcomes described above are occurring. This data collection event highlighted the commonalities of experiences of multiply marginalized students within the engineering college and helped them begin to effectively build power in larger numbers by collaborating with students marginalized in ways different from their own. The results of this study document the failure of neoliberal, corrective incremental methods to address structural inequities that plague marginalized engineering students from above. Instead, we demonstrate the ability of the students themselves to develop shared understanding and build power. Future work will further document this group's trajectory as they build the skills needed to organize for social change.

The group of undergraduate students who participated in the qualitative study is a microcosm of the people of the world as a whole. Women, racial minorities, and working class people together comprise the vast majority of the population in every state and nation but do not currently have agency in the application of engineering technology. A more accurate and universal understanding of the impact of identity on educational outcomes in engineering is one of the necessary precursors to the advocacy, theorizing, and organizing efforts that will make structural changes come to fruition. Through this process, engineering efforts can be undertaken by the marginalized majority in support of their own communities.

Until we are willing to contend with the underlying structural issues that lock individuals and families into cycles of oppression from within our roles as engineering educators, we will never be able to erase the injustices experienced by our students of marginalized identities. Critical and liberative pedagogies aim to dismantle oppressive systems through recognition of hegemonic structures, critical classroom discourse, and opportunities to build solidarity. In engineering, educators can and should contribute to liberative efforts by employing these pedagogical methods. Through an embrace of critical and liberative theories and their accompanying pedagogies, engineering educators and engineering education researchers can plant the seeds for change. We must restructure the goals of engineering education to include equity and solidarity and reshape the purpose of the engineering profession from profit maximization to transformative justice and the common good. When engineers develop the skills necessary to recognize and combat oppression, they will be able to work toward liberation for all oppressed peoples. Through pedagogical, research-based, and other efforts to apply critical theory to engineering education, we as educators can better position the field of engineering to support the development of a new social structure in which labor directly fulfills human needs and every sector of humanity achieves true liberation.

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